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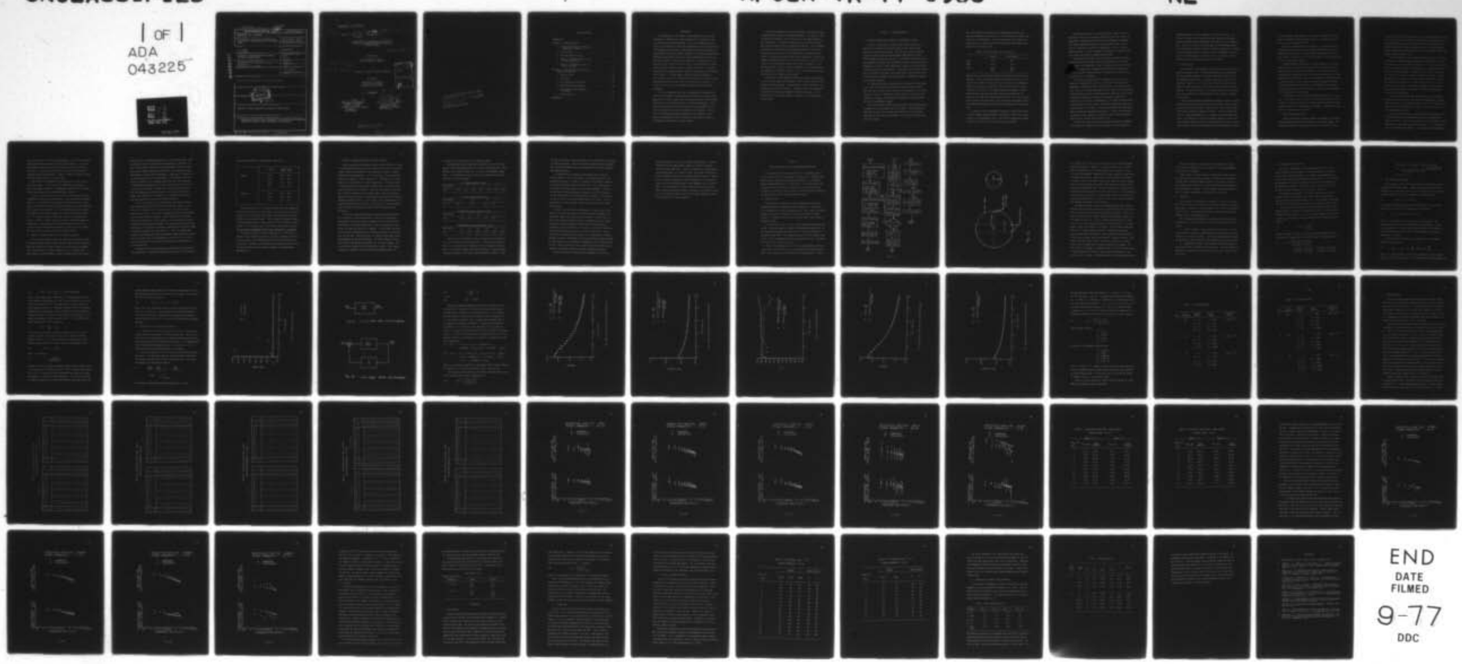

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR- 77-0966	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) The Development, Maintenance and Mathematical Description of Tracking Behavior in the Rhesus Monkey		5. TYPE OF REPORT & PERIOD COVERED Final Scientific Report Final--10/1/75 - 3/31/77
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D. F. McCoy P. K. Bhagat		8. CONTRACT OR GRANT NUMBER(s) AFOSR-75-2751
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Kentucky Research Foundation Lexington, Kentucky 40506		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2312/A2
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Officer of Scientific Research (NL) Building 410 Bolling A.F.B., D.C. 20332		12. REPORT DATE 6/15/77
		13. NUMBER OF PAGES 63
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Behavior, Tracking, Mathematical Description, Rhesus Monkey

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Procedures are described wherein Rhesus monkeys are trained on pursuit and compensatory tracking tasks. Parameters of these procedures are explored. Mathematical analysis of these methods is also reported.

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AFOSR-TR- 77-0966

Final Report, 1 Oct 75 - 31 Mar 77

AFOSR 75-2751 - 75

THE DEVELOPMENT, MAINTENANCE, AND MATHEMATICAL DESCRIPTION OF TRACKING BEHAVIOR IN MAN AND THE RHESUS MONKEY

2312 A2

Submitted to

United States Air Force
Office of Scientific Research

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by

University of Kentucky Research Foundation

on behalf of

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University of Kentucky
Lexington, Kentucky 40506

ACCESSION for	
NTIS	White Section ☑
DDC	Buff Section ☐
UNANNOUNCED	☐
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DISTRIBUTION/AVAILABILITY CODES	
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June, 1977

36p.

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INTRODUCTION

An understanding of the effects of environmental stress on human performance is essential for specifying man-machine system design and for predicting mission effectiveness. Noise, high temperature, acceleration, and vibration are among the environmental stressors which affect aircrew members during flight. These effects are seen as alteration of physiological function and general decrements in performance capabilities. Laboratory studies done with man are often compromised by the fact that only certain ranges of stress can be employed. One alternative is to develop a series of tasks similar to those of aircrew members or remote pilots and train subhuman primates to perform such tasks. This alternative offers the unique feature of enabling the application of stresses at all levels. It further enables certain surgical manipulations which afford access to the physiological and biochemical factors of which performance decrements under stress are assumed to be a function. It is only in this way that the fundamental mechanisms involved can be elucidated.

It is also noteworthy that with the emergence of the Remote Pilot Vehicle (RPV) concept, attention becomes redirected to the tracking task *per se*, and to the less obvious but nevertheless stressful factors which are specific to the tracking task (e.g., fatigue and boredom). Accordingly, the laboratory tracking situation has direct applicability to the RPV paradigm since it closely resembles that situation. In fact, results of tracking experiments conducted in the laboratory can be directly extrapolated to the RPV without the contaminating effects of physiological stresses due to vehicle dynamics.

The above mentioned goals can be achieved most efficiently through a viable program involving an integrated approach. One element in such an approach is modeling, a tool that can aid in the identification of basic mechanisms. The results of modeling efforts are best utilized when they are closely tied to an experimental program. This arrangement can produce an iterative process whereby the analytical results from models can serve as aids in the interpretation of experimental data, guides in planning future experiments, and as projections of results for studies too numerous, costly, or difficult to conduct. Similarly, the results of the experimental program can be used as "updates" for the modeling studies. Under this ideal arrangement, the iterative process can proceed at a relatively rapid rate. It is this rationale upon which the present research program was developed.

Specifically, several potential methods to produce tracking behavior in the Rhesus monkey were explored in order that the most efficient procedure could be produced. Once developed, various parameters of the method were studied experimentally. Concomitant with this advancement, a mathematical model was developed and applied to the data. A full description of each endeavor appears in Sections 1 and 2 respectively of this report.

SECTION 1.: TRACKING BEHAVIOR

A. TRANSITION FROM PURSUIT TRACKING TO COMPENSATORY TRACKING

In order to appreciate the significance of this manipulation, it should first be noted that the early phases of this project dealt exclusively with pursuit tracking. This was due to the fact that the original training procedures were developed under another contract (AFOSR F33615-72-C-1112) for this task. Furthermore, the pursuit tracking equipment had already been constructed, and while the more preferred compensatory system was under development, a series of pursuit tracking sessions was given to three animals. The purpose of this initial session was to re-establish asympototic performance levels which could be used as baseline data to compare with those obtained in subsequent compensatory tracking situations.

All animals received our standard series of pursuit tracking exposures. Each daily session was comprised of three 15-minute blocks. Each block was sectioned into 30 second trials separated by a 30 second intertrial interval. Although the precise effect of this set of time parameters is unknown, this particular combination of time variables has met with considerable success.

Prior to the shift, percent of time on target for the pursuit task averaged 96.4%, with a range from 92.6% to 99,8%. These values were based upon the last five sessions before the shift in which target width was 1.0 inch with an input signal of .122 cps and .163 cps (sum of two sine waves).

Next, these animals were placed on the compensatory tracking task, the basic parameters of which were a 1.0 inch target and a random input signal of .05 Hz bandwidth. Time on target scores were collected for each animal over a five session block, pursuit and compensatory scores appear in the following table.

PERCENT OF TIME ON TARGET, TOT (5 sessions)

		Pursuit		Compensatory
#065H		99.8		94.7
#065B		96.9		99.0
#476B		92.6		69.9
	$\overline{X}$	96.4	$\overline{X}$	87.5

Clearly, two of the three animals manifested negligible effects of the transfer. In fact, one animal appeared to improve slightly. For the third animal (#476B) the reduced time on target score for compensatory tracking is due solely to the first session during which this animal "tracked" at a mere 54%. This monkey improved considerably in subsequent sessions, and, when the first session was dropped from the analysis, TOT scores for the animal rose to 89.6%. With this corrected value inserted into the analysis, the group mean was elevated to 94.4%, which compares favorably with the 96.4% value obtained for the pursuit task.

In addition, and for comparative purposes, two naive animals were given the standard response shaping, followed by a block of five daily sessions on the compensatory task. Their time on target scores ranged from 76.4% to 83.0% ($\overline{X}$ of 87.2%) for the five-day period.

The overall conclusion to be drawn from this research is that no detrimental effects are in evidence following a shift from pursuit to compensatory tracking when the current set of parameters is employed. This finding agrees with Poulton's (1974) conclusion that in human tracking situations, the pursuit-to-compensatory shift can be made without decrement. It does, therefore, illustrate still another similarity between the human and subhuman tracking task.

Unfortunately, the other half of Poulton's conclusion regarding asymmetrical transfer between pursuit and compensatory tracking was not tested in this experiment. That is, because the primary mission of the present research was directed toward establishing compensatory tracking in pursuit trained animals, the reverse shift (compensatory-to-pursuit) was not attempted.

In addition, and based upon the comparison with the two control subjects, it appears that not only is the transfer from pursuit-to-compensatory tracking possible, the transfer is in the positive direction: That is, the three experimental animals appear to have benefited from the previous pursuit tracking experience since their scores ranged considerably higher than did those of the control subjects which received no such training. Parenthetically, it should be mentioned that at the conclusion of this project, the control animals were showing a steady increase in TOT scores. Thus, their previously mentioned scores were not based upon asymptotic performances. In fact, the acquisition functions for these subjects are similar to those of the experimental animals on the original pursuit tracking task.

Finally, the fact that the control subjects learned the compensatory task at all, attests to the fact that our training procedure is

indeed applicable to either compensatory or pursuit tracking. The critical features of this procedure have been spelled out elsewhere (Lafferty, Edwards, McCoy, McCutcheon, 1973) and will not be belabored here. Suffice it so say that the procedure we have developed appears to fit either task and that no special retraining procedures are required to train subhuman primates on either pursuit or compensatory tracking. It will be recalled that this feature, that of a universal training method, was one of the primary goals of this research.

B. TITRATED SHOCK

Our standard training procedure employed continuous high levels of shock at programmed rates. The presumed advantage of this technique was that immediate feedback was provided when errors occurred. Also, the parameters involved (e.g., frequency, intensity) could be easily specified. However, it is also true that shock administered in this manner has other properties which probably adversely affect tracking behavior. One obvious example is the skeletal reactions (e.g., thrashing, stick slamming, etc.) which accompany shock and which interfere with tracking.

The titration procedure represented an attempt to remove the above-mentioned emotional concomitants which shock produces, and yet retain shock as the controlling agent in these studies. For present purposes, the titration concept was applied as follows: When the subject made an error, shock was applied, but at a reduced (or perhaps nonaversive) level. The intensity of the shock increased, however, so long as the error existed. When the shock level became sufficiently high, the subject corrected the error by returning the controlled element to target.

In this situation, shock intensity was a direct function of error time. Under this condition, shock intensity began at 1 ma and increased at a rate of 1 ma to a maximum of 5 ma.

During the latter phases of this project, a titration shocker was purchased, and after several "false starts," programmed into the compensatory tracking system. One naive animal was shaped to hold, and later to move the control stick in the usual manner. It was then placed on the titration shock schedule.

Although premature conclusions are always dangerous, it does not appear that this subject was tracking as well as some other subjects which received the standard-shock treatment. This particular animal seemed to have learned more slowly, and maintained a consistently lower asympototic performance level than the "conventionally trained" animals. On the other hand, we have learned that great individual differences exist between Rhesus monkey subjects, and, therefore, another naive animal was undergoing training according to the same set of parameters at the termination of this project.

In principal, we believe that the titration technique is a viable one. At the same time, it is risky to draw conclusions at this point in time. Additional subjects are required along with certain schedule adjustments before firm conclusions can be drawn. Unfortunately, funds for this reseach were not available.

C. FOOD MAINTAINED TRACKING

Colony confinement, handling, chairing, confinement in the experiment chamber and shock are all stressful to the Rhesus monkey. This point was alluded to in the previous section. The overall effect of

such factors may be that a high stress level is produced which interferes with, and in some cases prohibits, the learning and maintenance of a complex and delicate task such as tracking. While the above-described titration procedure attempted to retain shock as a reinforcing agent through a reduction in shock intensity, the present section focuses upon another source of control, food.

The basic features of this procedure involved training the subject to maintain a controlled element on target for progressively longer time periods in order to obtain food pellets. In order to avoid satiation, the subject was given food pellets only at programmed intervals during the tracking session. At other times, a tone was substituted for food. By virtue of its previous association with food, the tone has acquired the capactiy to reinforce behavior secondarily. Actual tone-food pairing occurred on a fixed ratio basis of 5:1. For each criterion time on target, the tone was presented. Food accompanied the tone (and maintained its strength as a conditioned reinforcer) on every fifth presentation.

The first animal studied was trained jointly on food and shock. When these reinforcing agents were later made independent, it became clear that shock was the overrriding agent: That is; the subject would not work for food independently of shock, but would track to avoid shock independently of food.

Later in the grant period, a second animal was pretrained on the FR5 tone-food pairing and subsequently placed in the compensatory tracking situation. After a few sessions this animal's behavior became highly erratic, and TOT scores diminished rapidly. Mild food deprivation did not remedy the situation. It appeared that the conditioned

(tone) was losing its reinforcing effectiveness. At this time, tracking sessions were halted and tone-food pairings were resumed. In spite of this additional training, the tone did not appear to be an effective reinforcer. It was also discovered that the animal was consuming progressively fewer sucrose pellets. Finally, it would not longer eat them when made freely available in the home cage.

Other animals have evidenced similar behavior with other sorts of reinforcing agents. The decline in the reinforcing effectiveness of these conventional reinforcers is undoubtedly responsible for the highly erratic data yielded in the food-reinforcement situation.

The fact that we have not, at this point, established clearly that compensatory tracking can be maintained on a food reinforcement schedule, does not, in our opinion, vitiate against the basic premise of the procedure. Any behavior is only as strong and reliable as are the conditions used to support that behavior. If the reinforcers upon which the behavior depends lose their effectiveness, the behavioral output will diminish. This does not, however, reduce the utility of the food-tracking premise. Rather, it simply indicates that other reinforcing agents must be employed. At the conclusion of the grant period, we were of the opinion that this problem had been solved but, due to a lack of supporting funds, we were not able to pursue the problem further.

D. HUMAN VS. SUBHUMAN OPERATORS IN TWO TRACKING SITUATIONS

As part of our program to study the comparative similarities and/or differences between human and monkey operators under identical situations, data were collected from these two species for both pursuit and compensatory tracking tasks. In this connection, it is of interest that a paper appeared recently (Bachman, Jaeger, and Newsom 1976) which focused

upon the issue of man-monkey comparisons in a tracking situation. Using an argument similar to that which we have employed for some time (i.e. that a monkey model is necessary for the application of stress to man), these authors argued convincingly that we must first demonstrate that these species do show similar performances. Based upon a primate-training task quite similar to that discovered in our laboratory some four years ago, Bachman, et al. produced results which do lend credibility to the monkey-man extrapolation since the two species did perform similarly on the task studies. However, their results were based solely upon the compensatory tracking situation. Our present results both support and extend those of Bachman et al., since our data are based upon both compensatory and pursuit tracking situations.

In the initial phase of the investigation, four humans and three Rhesus monkeys were studied in the pursuit tracking situation. Target size was 1.0 inches and a sum of two sine waves (.122 and .163 cps) was used as the input. Trials were 30 seconds in duration and separated by a 30 second intertrial interval. Three fifteen-trial blocks were given to each subject in a single session. For the monkeys "off target" performances were punished with shock. For the humans, these errors were punished on an error-cost basis which was subtracted from the total amount of money ($3 maximum) which they could earn. Next, all subjects were studied in the compensatory tracking situation, characterized by a target size of 1.0 inches and an input bandwidth varying from .05 to .15 cps. Error contingencies, trial durations and intertrial intervals were as in the former task.

Although the fine-grained behavioral outputs remain to be analyzed and mathematized, a preliminary evaluation can be made from the following

table based on percent of time-on-target scores (TOT).

	Pursuit	Compensatory .05	Compensatory .15
Humans	99.8	99.9	99.3
	99.6	99.5	99.3
	98.5	98.9	98.5
	96.7	97.6	97.4
Monkeys	99.8	94.7	94.2
	96.9	99.0	98.4
	92.6	89.6	90.8

From the above table, it is clear that both human and subhuman operators perform quite well on both tasks. Very few errors occur in any situation. More importantly, both humans and monkeys show negligible effects of the parameter changes. The functional relationship between TOT and parameter changes is quite similar for each individual organism studied. It is the point which is of critical significance; viz that the functional relationships are the same, regardless of the species.

The results, along with those of Bachman et al., offer strong support for the contention that human and monkey operators are similar on the two tasks. Any differences which exist are quantitative, not qualitative. Therefore, the emotionally-based argument offered by some that man and monkey are functionally different is not supported by empirical fact.

E. EFFECTS OF TRANQUILIZING DRUGS ON PURSUIT TRACKING

Before discarding the mechanical pursuit tracking facility in favor of the compensatory system, two animals were given a series of tracking sessions under various dosages of two tranquilizing agents, chlorpromazene (CPZ) and pentobarbital. CPZ is classified as an antipsychotic drug and is viewed as a "major tranquilizer". Pentobarbital is a barbituate, and is classified as a "minor tranquilizer". Relatively little is known regarding the effectiveness of these drugs on complex pyschomotor activities such as tracking. Therefore, one purpose of the study was to determine whether the two chemical agents would have different effects on tracking ability. Another purpose was related to the earlier-mentioned "emotional effects" of high stress levels associated with the shock-maintained tracking situation. Specifically, it seemed possible that low dosages of tranquilizers could actually improve tracking efficiency.

As with many psychopharmacological experiments, the general plan was to establish a baseline, administer a drug at a low dose level, and gradually increase the dose on subsequent drug sessions until the performance level changed significantly. Next, for purposes of replication, the lower case levels were repeated. In the present situation, drugs were given intramuscularly at irregular intervals, but never more than one each week. Several non-drug, or placebo sessions were always spaced between any two drug conditions. One animal (Hoppy) was given CPZ at several dosages and the pentobarbital at several dosages. The drug order was reversed for the second animal, Big Boy. Both subjects received the "standard" tracking conditions described earlier (i.e.,

30 second trials, 30 second ITI, full-intensity shock).

Computer analysis and mathematical description of the "fine grain" aspects of the drug-produced behaviors is yet to be accomplished. Nevertheless, time on target scores, TOT (in terms of percentages), appear below. It is important to realize that the drug dosages were given in the order in which they appear.

CPZ (Hoppy) BASELINE = 99.8%

Dose (Mg/Kg)	.2	.5	1.0	.75	.5	.35	.2
% TOT	97.1	97.7	41.2	32.8	41.0	54.9	51.8

CPZ (Big Boy) BASELINE = 96.3%

Dose (Mg/Kg)	.2	.35	.2	.15
% TOT	92.2	40.0	76.2	95.2

PENTOBARBITAL (Hoppy) BASELINE = 99.8%

Dose (Mg/Kg)	5.0	8.0	1.20	3.5	5.0
% TOT	94.0	74.7	71.4	58.1	59.3

PENTOBARBITAL (Big Boy) BASELINE = 96.3%

Dose (Mg/Kg)	5.0	8.0	12.0	15.0	8.0	5.0
% TOT	90.5	88.0	90.0	41.0	86.3	89.1

Looking first at the effect of CPZ, the lowest dose (.2 Mg/Kg) had only a slight effect on tracking efficiency. This was true for both animals. At this point, the similarity of their reactions to the drug ended. For one animal (Hoppy) increased doses up to 1.0 Mg/Kg produced systematic decreases in TOT scores. More interesting, however, is the

fact that the return to lower dose levels was not accompanied by increases in tracking efficiency. Thus, this animal's response was dose dependent until tracking had become severly attenuated, but it was dose independent beyond that point.

A different picture emerged with the second animal (Big Boy) studied under CPZ. In the first place, this monkey was clearly more sensitive to the drug. A dose of .35 Mg/Kg was sufficient to suppress his tracking efficiency below the chance level. More interestingly, this animal's behavior appears to be more dose-dependent. The return to lower doses yielded progressive increases in tracking efficiency. The only discrepency in this generalization occurred at .2 Mg/Kg where TOT was 16% less on the second administration of this dose. This was due mainly to a single episode in which the animal removed his hands from the stick.

Consider now, the effect of pentobarbital. Clearly, much larger doses of this agent were required to affect behavior measurably. For one animal, Hoppy, the effect was much the same as with CPZ; that is, TOT scores decreased progressively with increased dose level. Beyond this point, however, decreases in dosage were not accompanied by increases in tracking efficiency. TOT scores at 3.5 and 5.0 Mg/Kg were both considerably below that at the initial 5.0 dose level. Again, this animal's tracking efficiency was at first decreased by increasing dosages, but later, TOT remained low and was unrelated to dose magnitude. In sharp contrast, was the effect of pentobarbital on the second animal, Big Boy. Again, the effect of dose strength on tracking efficiency was inverse; as dose level increased, tracking efficiency decreased.

Clearly, the effect of both drugs was dependent as much on the

individual animal as it was on the specific dose employed. The most interesting case is Hoppy who was unable to recover his tracking efficiency at any dose level. Still, this subject did track effectively on non-drug days. As a matter of fact, this animal's performance actually improved slightly over successive baseline sessions. Perhaps, for this animal, any quantity of drug functioned as a discriminative stimulus and its performance became "state dependent" (e.g., Overton, 1967). This finding may also reflect the possibility that the two animals studied used quite different strategies in learning and performing in the tracking situation, and that the drugs studied here selectively affected one of these mechanisms.

SECTION II

DATA ACQUISITION, ANALYSIS AND MATHEMATICAL MODELING

This section describes the development of a 5 parameter model to fit the primate data in a compensatory tracking task. A computer iterative scheme of determining the optimal parameters of a given model based on experimental data is also detailed. This section begins with a description of the electronic system used in tracking experiments followed by a overview of process control, data acquisition and analysis, and model identificaiton scheme and modeling results.

A. TRACKING SYSTEM

The electronic system used in tracking experiments was custom-designed and built at Wenner-Gren Research Laboratory. The machine is fully programmable in that all parameters like "Test", "Rest" and "Grace" periods, and number of "Test/Rest" cycles can be externally preprogrammed. In addition, the machine can be used either in the Pursuit or Compensatory mode.

The flow chart of Fig. 2.1 gives a block diagram description of the system. The system primarily consists of hybrid-analog and digital signal conditioners designed to control the X, Y and Z axis display of a Cathode Ray Tube (CRT). The stationary pattern of the CRT screen, shown in Fig. 2.2a, is generated internally using analog circuits. The scheme used to do this is shown in Fig. 2.2b.

Notice that the pattern of Fig. 2.2b can be generated on a CRT by simply using r_1 Sin ωt and r_2 Sin ωt on horizontal axis display control and r_1 Cos ωt and r_2 Cos ωt on vertical-axis display control. Both r_1

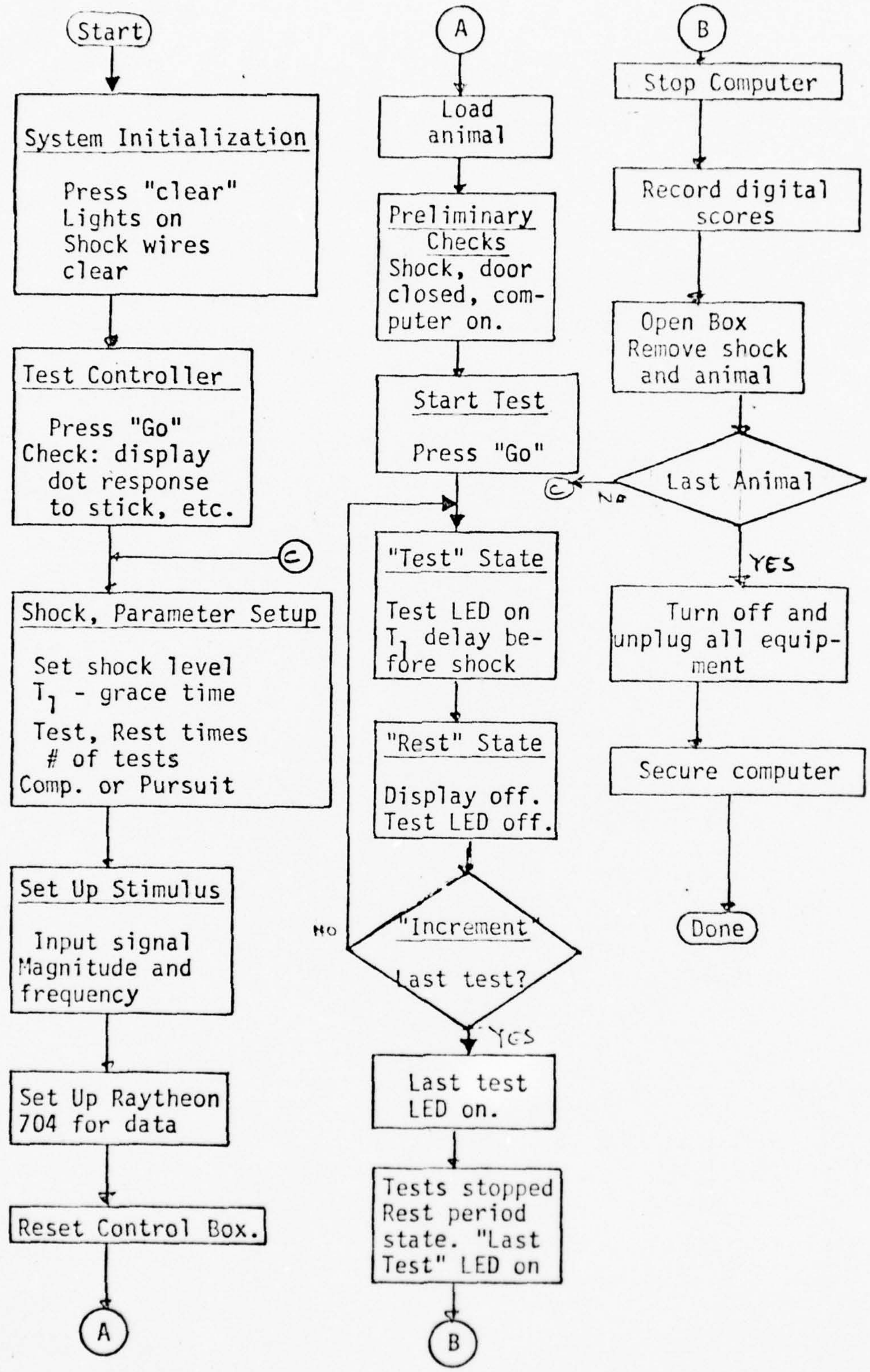
Start
System Initialization
Press "clear"
Lights on
Shock wires
clear
Test Controller
Press "Go"
Check: display
dot response
to stick, etc.
C
Shock, Parameter Setup
Set shock level
T1 - grace time
Test, Rest times
# of tests
Comp. or Pursuit
Set Up Stimulus
Input signal
Magnitude and
frequency
Set Up Raytheon
704 for data
Reset Control Box.
A
A
Load
animal
Preliminary
Checks
Shock, door
closed, computer on.
Start Test
Press "Go"
"Test" State
Test LED on
T1 delay before shock
"Rest" State
Display off.
Test LED off.
"Increment"
Last test?
NO
YES
Last test
LED on.
Tests stopped
Rest period
state. "Last
Test" LED on
B
B
Stop Computer
Record digital
scores
Open Box
Remove shock
and animal
Last Animal
C
NO
YES
Turn off and
unplug all equipment
Secure computer
Done

Fig. 2.1

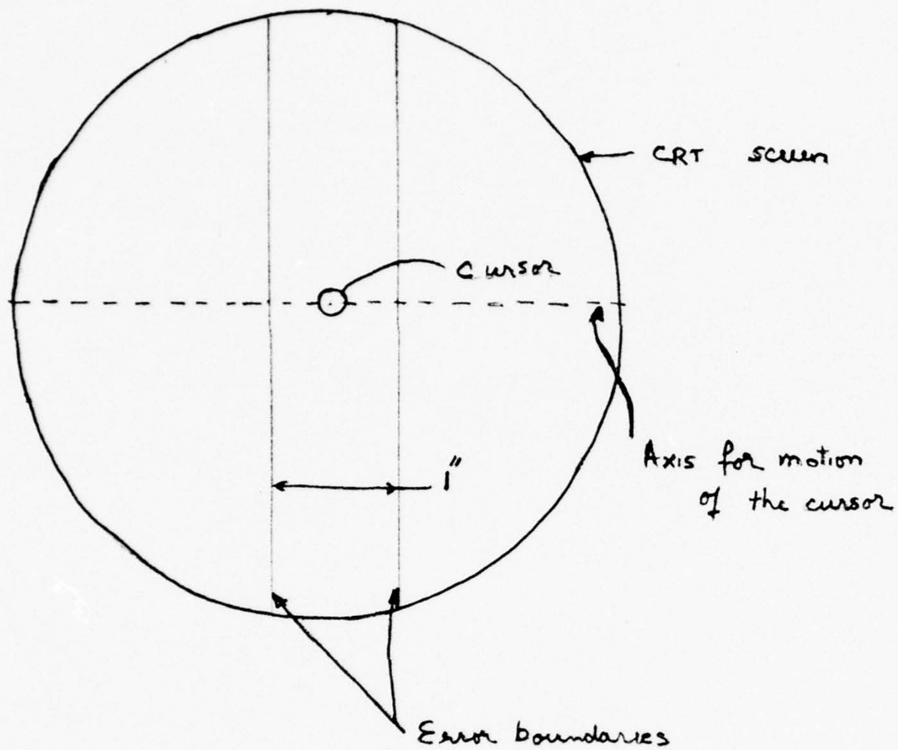

Fig. 2.2a

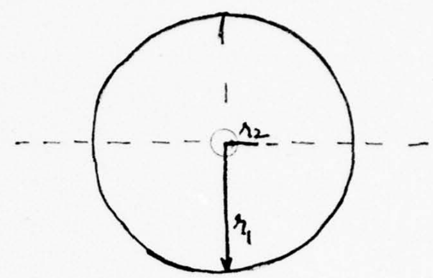

Fig 2.2b

r_1 Sin ωt and r_2 Sin ωt, and r_1 Cos ωt and r_2 Cos ωt are time-multiplexed using Z-axis control. However, if r_2 on the vertical axis is greatly amplified compared to r_2 on the horizontal axis, the pattern of Fig. 2.2a would be generated. Depending on the mode, pursuit or compensatory, the analog input signal, stimulus x(t), is used to control the motion of vertical lines or the central cursor (dot) along the X-axis, respectively. The stick output y(t) controls the motion of the cursor both in pursuit and compensatory modes. An error signal e(t) is generated when the cursor crosses boundary limits which turns shock on and simultaneously causes the cursor to blink. All these signals x(t), y(t) and e(t) are internally conditioned to lie within 0-2 volts and are made available to the Raytheon-704 computer for digitization.

The digital section is basically a quad-time-state logic machine. External manual controls "Clear" and "Go" enable the machine to be reset, and initialized before starting the experimental session. "Clear" signals the machine into the "Ready" state and simultaneously triggers the CRT pattern of Fig. 2.2a. The "Go" signal takes the machine to "Test" state. In this state the machine waits for "Grace" period T_1, and then checks to see if the subject is on target. In an off target condition, the cursor is caused to flash and shock is applied to the subject. Shock continues until the subject is back on target at which time both light-blinks and shock signals are turned off. During the entire "Test" period the machine keeps track of time and at the end of T_2 seconds "Rest" state is entered and all activity ceases for T_3 seconds. The "Rest" state is followed by "Increment" state in which the machine checks if preset numbers of "Test/Rest" cycles have been completed, if not, a new cycle is initiated. At the end of the last cycle the machine halts.

The "Grace" period T_1 may be preset as a multiple of 1 second. "Test" and "Rest" periods T_2 and T_3 respectively can be preprogrammed as multiples of 10 seconds.

1. Random Inputs: The input used for exciting the system (causing the cursor to move) was Gaussian-random in nature and was derived from a Random Signal generator (Hewlett Packard). The primary reason for using random input signals was to remove the element of predictability from the operator's response. In this research, the analog random signals of frequency bandwidths 0.05 Hz and 0.15 Hz were used.

B. EXPERIMENT

The main body of the experiment consisted of a series of runs covering the pursuit task initially and then gradually changing to compensatory tasks. The range of input frequencies was very low, only extending to 0.15 Hz. This was done to establish a data base in the lowest frequency range, disregarded thus far.

Both in pursuit and compensatory tracking tasks the animals were restrained in a chair in full view of a control stick and CRT target display.

1. Pursuit Tracking: The two vertical lines of Fig. 2.2a were moved either in a regular or random fashion, along the X-axis under the influence of an external stimulus. Test animals were required to maneuver the control stick to keep the cursor between the two vertical lines.

2. Compensatroy Tracking: The external stimulus was applied to the cursor forcing it outside the vertical lines. The test animals were required to manipulate the stick to position the cursor within the vertical lines.

C. DATA ACQUISITION AND ANALYSIS

During each experimental session, random input $x(t)$ to the controlled element and stick output $y(t)$ were digitized every 16 msecs on the Raytheon 704 digital computer. The computer was programmed to recognize "Rest" periods and discontinue data acquisition. In brief, data was recorded for 15 minutes on magnetic tapes for off-line analysis on the IBM 370/165 computer. The sampling rate of 16 msec was chosen to include all higher frequencies in the subject's response.

For data analysis purposes, the magnetic tapes were taken to the Computer Center for evaluating a describing function using programs based on Time-series-analysis (Gupta, 1977). This program was developed for use on IBM 370/165, using subroutines from literature (Reid, 1969).

The first part of the program combines subroutines FRTRM, SORT6, CRSCOR and PSD, to evaluate cross-spectral estimates Φ_{io} (cross-spectra between input and output) and Φ_{ie} (cross-spectra between input and error). Φ_{io} and Φ_{ie} estimates were used to calculate the describing function as given by

2.1 $$Y(j\omega) = \frac{\Phi_{io}\,(j\omega)}{\Phi_{ie}\,(j\omega)}$$

Since in Equation 2.1, both Φ_{io} and Φ_{ie} are complex numbers, they can be combined to express $Y(j\omega)$ as a series of real and imaginary parts.

2.2 $$Y(j\omega) = \frac{\mathrm{Re}\,[\Phi_{io}] + j\ \mathrm{Im}\,[\Phi_{io}]}{\mathrm{Re}\,[\Phi_{io}] + j\ \mathrm{Im}\,[\Phi_{ie}]}$$

$$= \frac{\mathrm{Re}\,[\Phi_{io}] + j\ \mathrm{Im}\,[\Phi_{io}]}{\mathrm{Re}\,[\Phi_{ie}] + j\ \mathrm{Im}\,[\Phi_{ie}]} \quad \frac{\mathrm{Re}\,[\Phi_{ie}] - j\ \mathrm{Im}\,[\Phi_{ie}]}{\mathrm{Re}\,[\Phi_{ie}] - j\ \mathrm{Im}\,[\Phi_{ie}]}$$

$$= \frac{(\text{Re}\,[\Phi_{io}])^2 + (\text{Im}\,[\Phi_{ie}])^2 + j(\text{Re}[\Phi_{ie}]\,.\,\text{Im}[\Phi_{io}] - \text{Re}[\Phi_{io}].\text{Im}[\Phi_{ie}])}{(\text{Re}\,[\Phi_{ie}])^2 + (\text{Im}\,[\Phi_{ie}])^2}$$

$$= Y'\,(\omega) + j\,Y''\,(\omega)$$

D. MODEL IDENTIFICATION SCHEME

The last phase of the analysis was matching the describing function estimates with a suitable model. Model identification starts with the assumption of a known model based on a visual judgement. Since the model transfer function $G(j\omega)$ can be expressed as a complex number:

2.3 $$G(j\omega) = G'(\omega) + j\,G''(\omega)$$

an alogrithm was devised to determine optimal values of various model parameters to minimize the sum squared error S *defined by*

2.4 $$S\,(\overline{A}) = \sum_i (G_i' - Y_i')^2 + (G_i'' - Y_i'')^2$$

where i is a frequency index, G_i' and G_i'' are data computed for the assumed model and Y_i' and Y_i'' are experimentally observed data. G_i' and G_i'' are computed for the chosen model using arbitrarily chosen values of *unknown parameters* $\overline{A}$, the dimension of which depends on the number of parameters in the model.

Differentiation of Equation 2.4 with respect to a given unknown parameter A_j is given by

2.5 $$\frac{\partial S}{\partial A_j} = 2\sum_i (G_i' - Y_i')\,\frac{\partial G_i'}{\partial A_j} + 2(G_i'' - Y_i'')\,\frac{\partial G_i''}{\partial A_j}$$

Since S is a function of $\overline{A}$, a Taylor series expansion in terms of known values of S and $\overline{A}^\circ$ may be made. ($\overline{A}^\circ$ is the initially chosen parameter set)

$$2.6 \qquad S(\overline{A}) = S(\overline{A}^\circ) + \frac{\partial S}{\partial A_j} A_j + \text{higher order trms}$$

Thus if higher order terms in Equation 2.6 can be neglected, an interactive program using Equations 2.2 and 2.3 may be devised such that $S(\overline{A})$ tends to zero (perfect fit). The program begins with an arbitrarily chosen parameter vector, $\overline{A}^\circ$. The upper and lower limits on the unkonwn parameters are required both to limit the search area and to physically interpret the data. The function value, $S(\overline{A}^\circ)$, G_i', G_i'' and $\frac{\partial S}{\partial A_j}$ are computed using Equation 2.6 and the chosen model. If $S(\overline{A}^\circ)$ and the magnitude of the gradient, $\overline{G}(\overline{A}^\circ)$, defined by,

$$2.7 \qquad \overline{G}(\overline{A}^\circ) = \left(\frac{\partial S}{\partial A_1}, \frac{\partial S}{\partial A_2}, \ldots\right)^T$$

are less than a specified tolerance the computer search for a local minima is over and a new one can be made with a different starting parameter vector. This is usually not the case whence a move in the negative gradient direction is made to define a new parameter vector

$$2.8 \qquad \overline{A}^n = \overline{A}^\circ - \alpha\, \overline{G}(\overline{A}^\circ)$$

where α is defined by

$$2.9 \qquad \alpha = \frac{S(\overline{A}^\circ)}{< \overline{G}(\overline{A}^\circ), \overline{G}(\overline{A}^\circ) >}$$

Equations 2.8 and 2.9 define the steepest descent formula (McGhee, 1967). At the new vector $\overline{A}^n$ the curve fit error $S(\overline{A}^n)$ is computed and compared with $S(\overline{A}^\circ)$. If the error has been reduced the new values are assumed and Equations 2.8 and 2.9 are used recursively. In the event the steepest descent method fails, a second order gradient technique known as the

Newton-Raphson technique (McGhee, 1967) has been incorporated which has good convergence properties in the vicinity of a minima. The new vector $\bar{A}^n$ with this formula is given by

$$\bar{A}^n = \bar{A}^\circ - [\Phi^T \Phi + \Theta^T \Theta]^{-1} \bar{G}(\bar{A}^\circ) \tag{2.10}$$

where Φ and Θ are rectangular matrices of partial derivatives of error terms $(G_i' - Y_i')$ and $(G_i'' - Y_i'')$ with respect to the unknown parameters. The process of iterative minimization of sum-squared error continues until no further reduction in S is possible with both the above gradient techniques.

E. VERIFICATION OF DATA REDUCTION TECHNIQUES

In order to test the program's ability to measure a linear system transfer function, three types of simulations were made. The first simulation to test auto-power-spectral estimates was effected by digitizing two sinusoidal waveforms of frequencies 2 Hz and 6 Hz. The program identified the predominant frequencies close to 2 Hz and 6 Hz. Fig. 2.3 shows power spectral estimates predicted by the program.

The second simulation of Fig. 2.4 was aimed at identifying an open loop system. The open loop system was simulated digitally using both the standard z-transform and bilinear z-form techniques. The z-transform equation for the system is given by

$$\frac{Y(z)}{X(z)} = \left.\frac{-10}{s-a}\right|_{z = e^{sT}} = \frac{-10T}{1-e^{-aT}z^{-1}} \tag{2.11}$$

where $a = 3$
$T = 16$ msec

The bilinear z-form equations for the system of Fig. 2.3 are

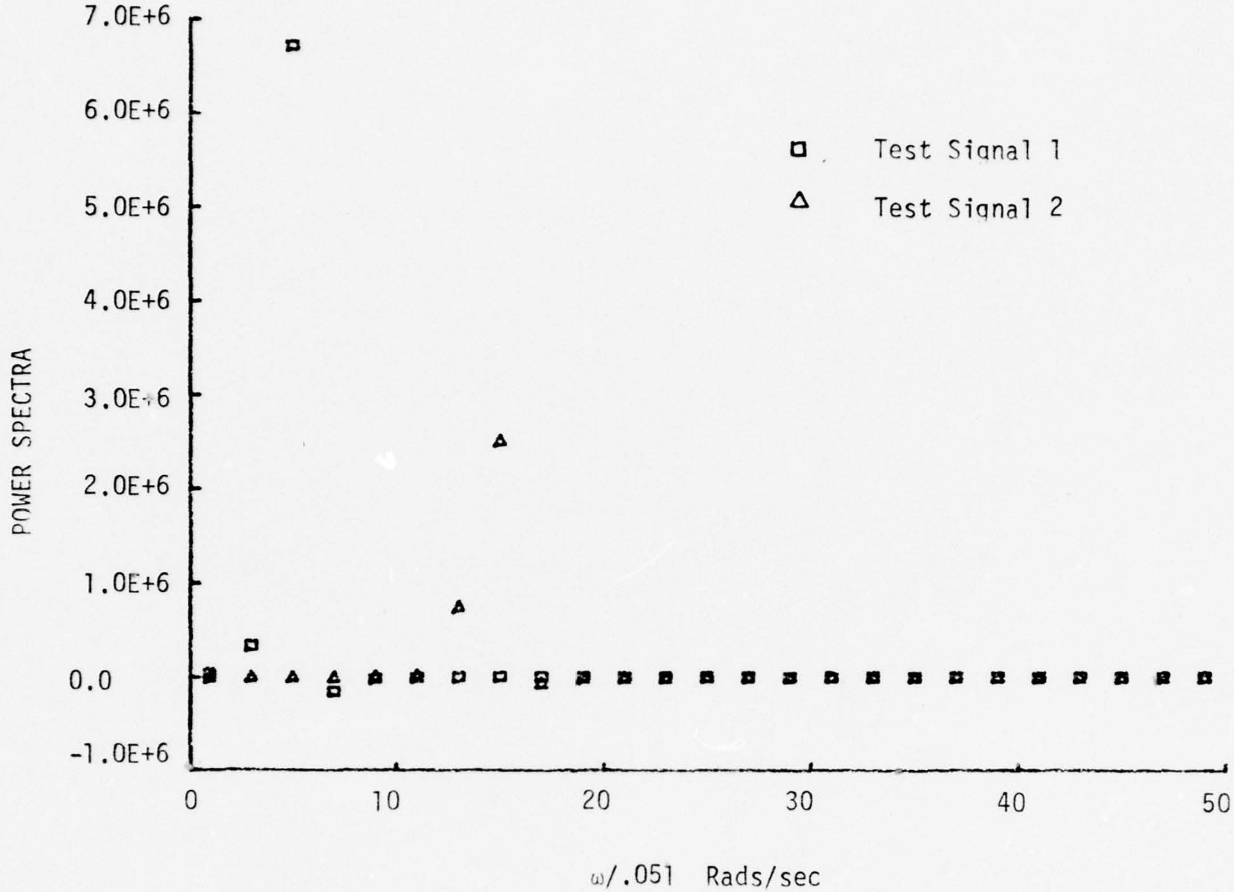

Fig. 2.3 Frequency Identification

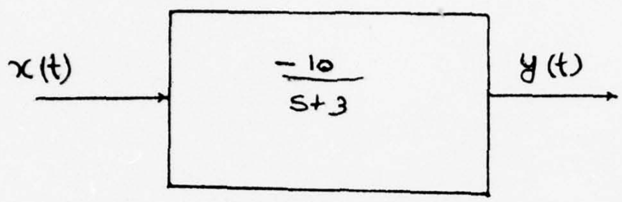

Fig 2.4 - Linear System (Open Loop) Identification

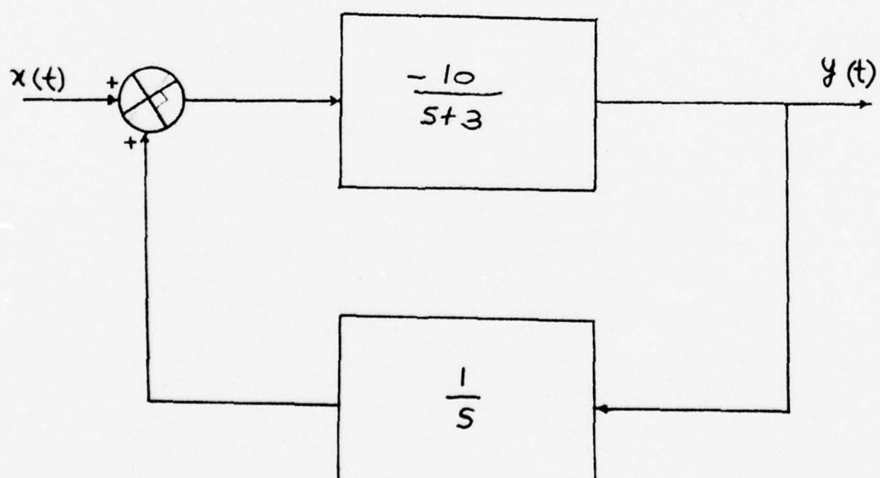

Fig 2.5 - Linear System (Closed loop) Identification

2.12 $$S = \frac{1-z^{-1}}{1+z^{-1}} \quad \frac{2}{T}$$

and

2.13 $$\frac{\omega_D T}{2} = \tan \frac{\omega T}{T}$$

Actual and observed magnitude and phase plots are shown in Figs. 2.6a and 2.6b. A comparison of the results was made with a program developed at the University of California (BMD 02T). It was observed that our programs fitted the actual results to within an accuracy of 2%. The results are shown in Fig. 2.7 where the correlation index ρ^2 is computed as a function of frequency. It should also be noted that the cumulative ρ^2 is very nearly .99, indicating that the system is linear. In order to verify the program's ability to identify an unknown system in a closed loop configuration, the system shown in Fig. 2.5 was digitally simulated using Equations 2.14 and 2.15 to generate Y(kT) and E(kT) respectively.

2.14 $$Y(kT) = \{1.323\ x(k-2) - x(k) + 7.9241088\ Y(k-1) - (4.0379456 - .1232\omega_D)\ Y(k-2)\} / (4.0379456 + .1232\omega_D)$$

2.15 $$E\ (kT) = \{\ (4.1 + .1232\omega_D)\ x(k) - 8.0\ x(k-1) + (4.0 - .1232\omega_D)\ x(k-2) + 7.9241088\ e(k-1) - (4.0379456 - .1232\omega_D)\ Y\ (k-2)\ \} / (4.0379456 + .1232\omega_D)$$

Where ω_D is the digital equivalent of the analog cutoff frequency defined by Equation 2.13. The results are shown in Figs. 2.8a and 2.8b.

The program was found convergent for various starting values chosen for a known 4-parameter model of Equation 2.16.

2.16 $$G(j\omega) = \frac{e^{-\tau s}\ (1 + T_1 s)}{(1+T_2 s)(1+T_3 s)}$$

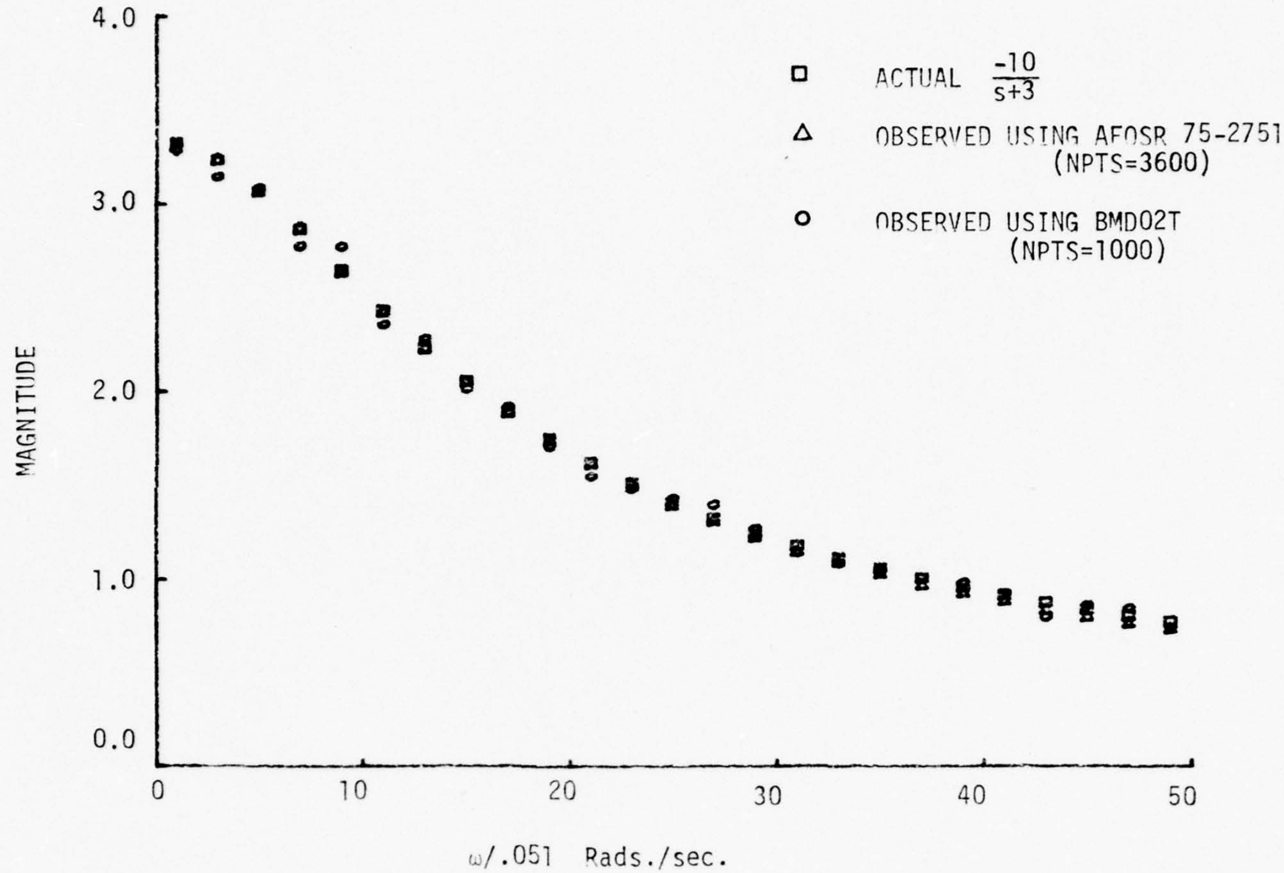

Fig. 2.6a Linear System (Open Loop) Identification

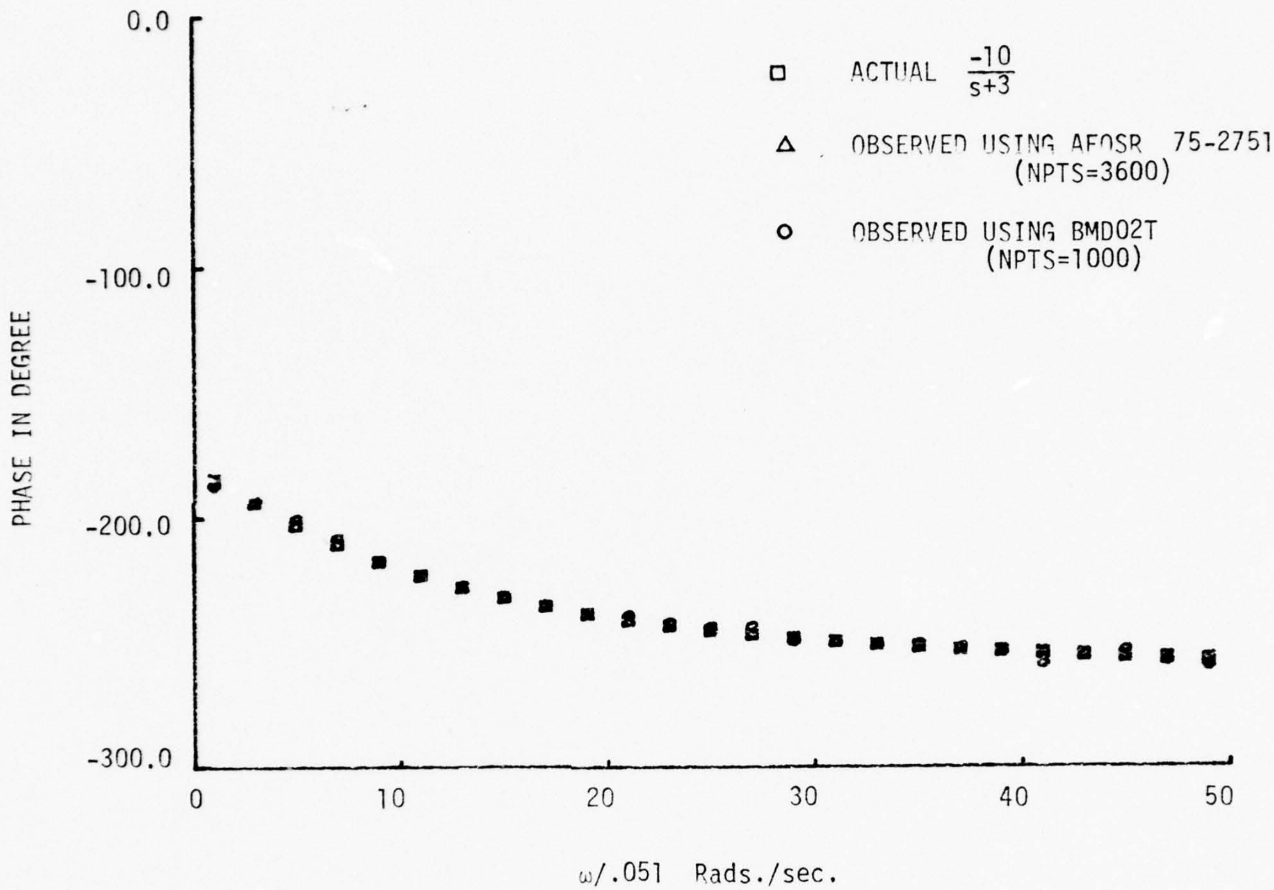

Fig. 2.6b Linear System (Open Loop) Identification

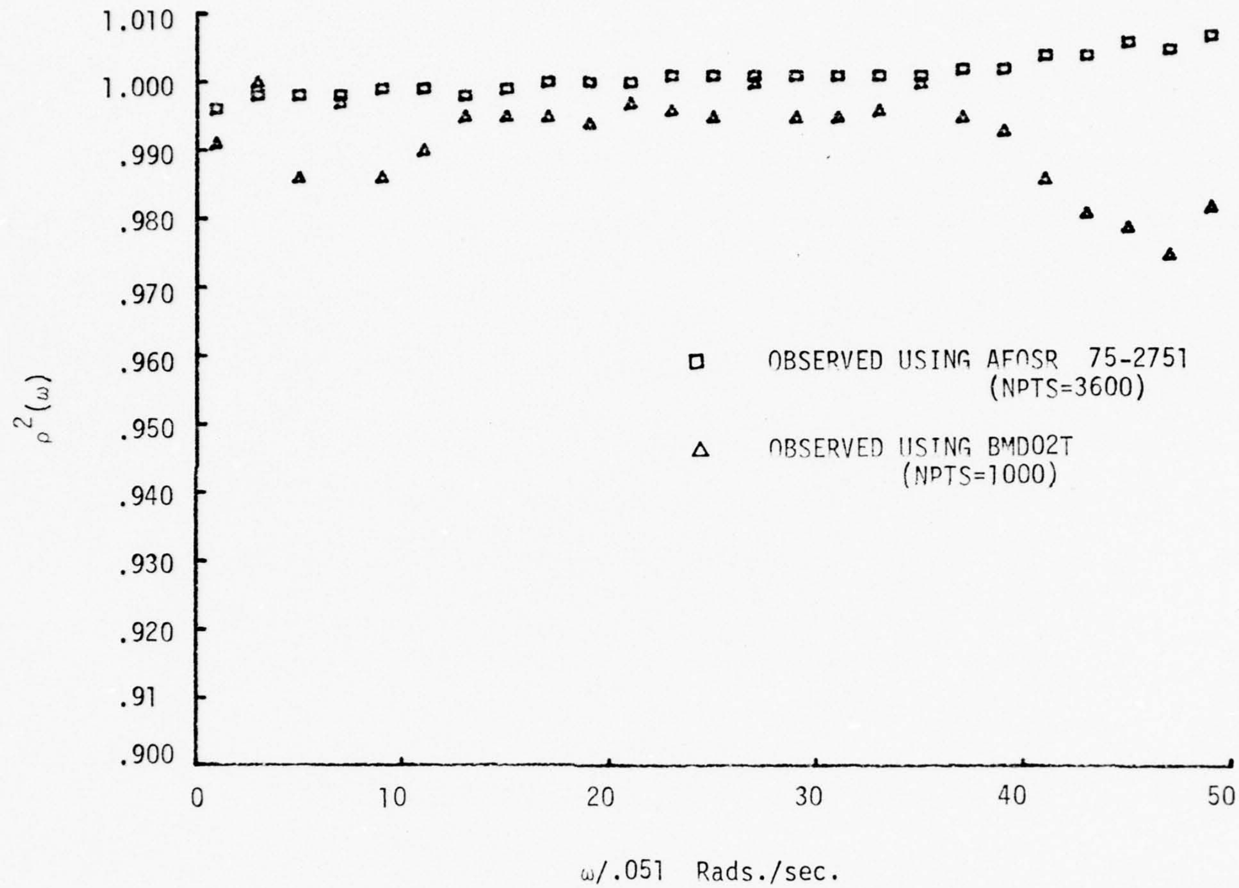

Fig. 2.7 Correlation Coefficients

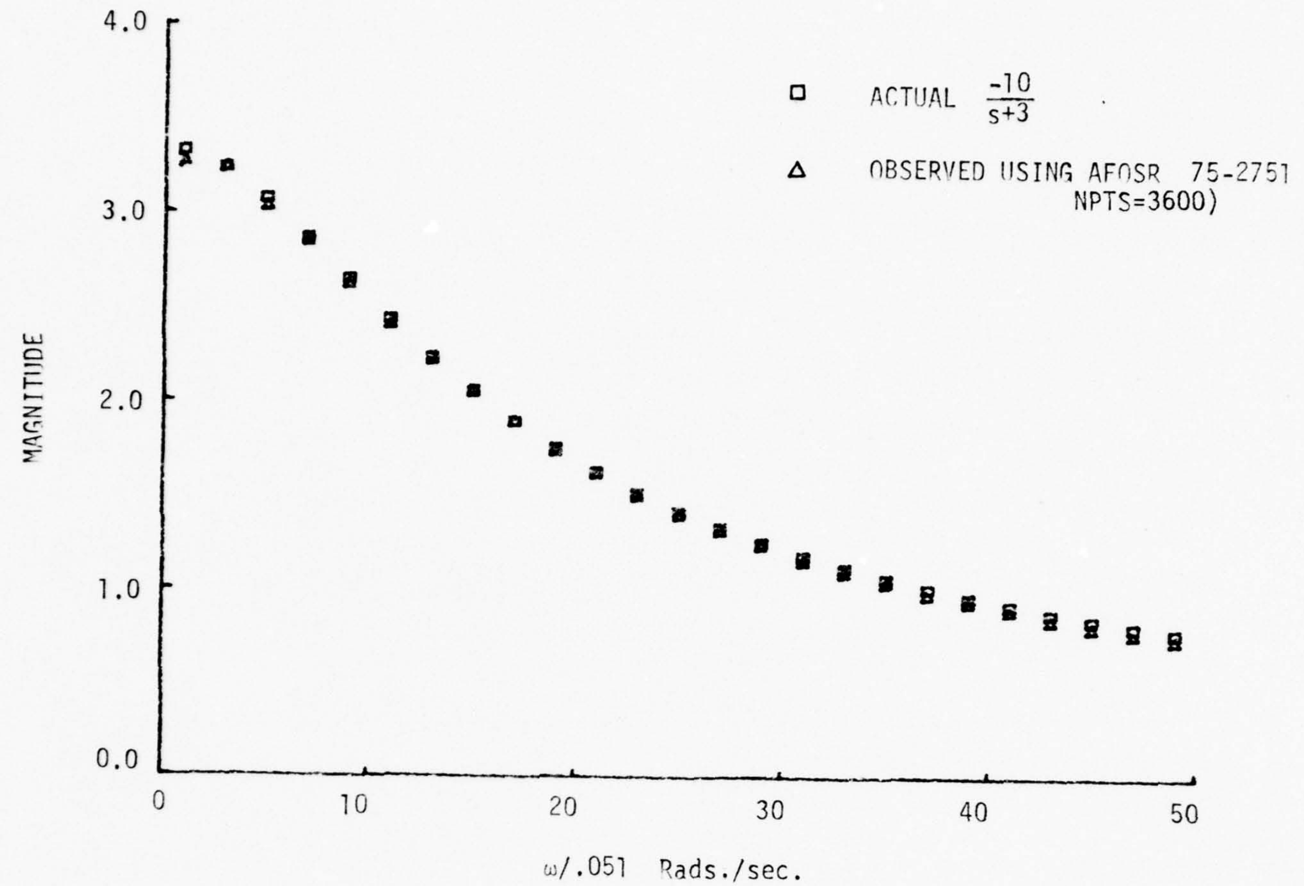

Fig. 2.8a Linear System (Closed Loop) Identification

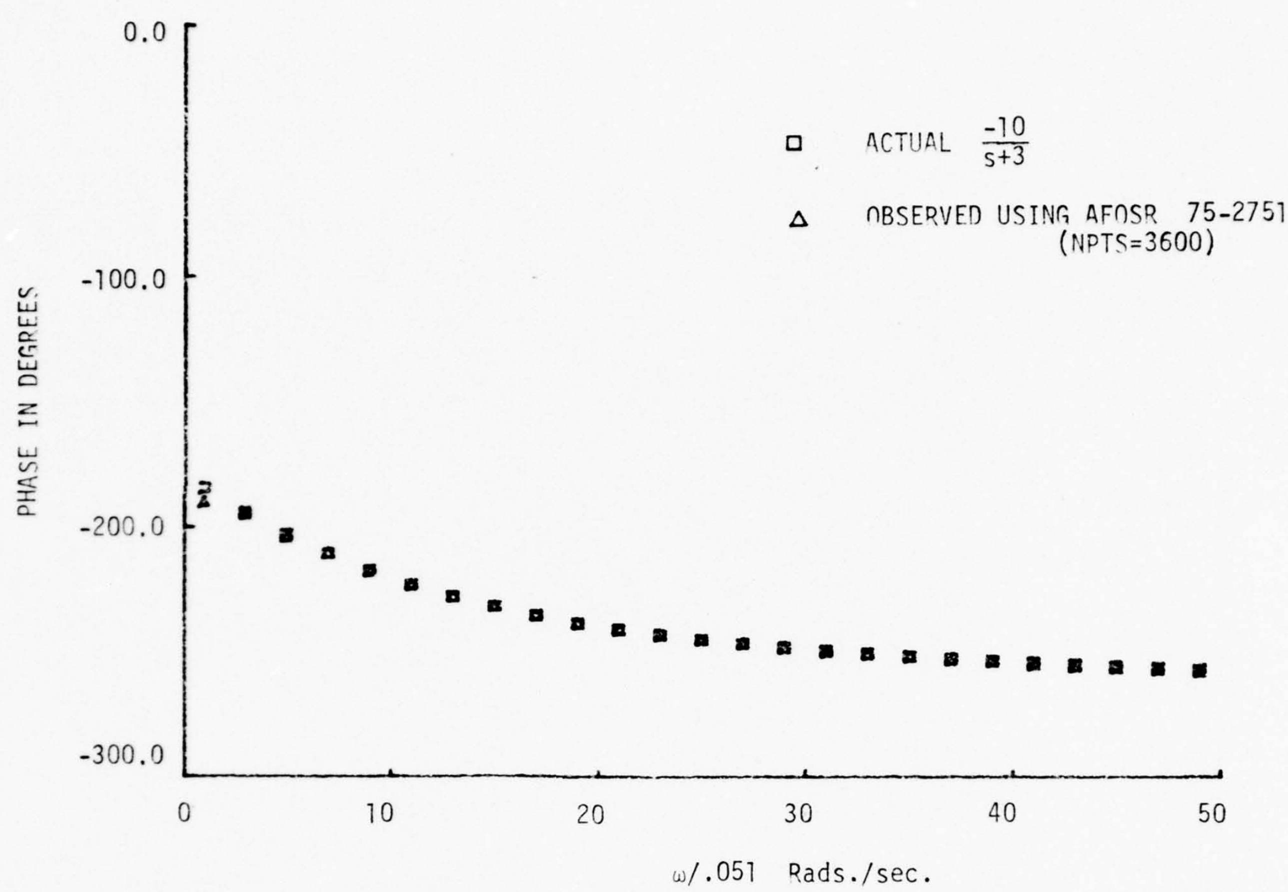

Fig. 2.8b Linear System (Closed Loop) Identification

The model parameter values were chosen as $\tau = 0.2$ sec, $T_1 = 0.2$ sec, $T_2 = 0.5$ sec, and $T_3 = 5.0$ sec. The program identified these parameters as $\tau = 0.19997$, $T_1 = 0.19997$, $T_2 = 0.50005$ and $T_3 = 4.9950$ starting with the arbitrarily chosen values of $\tau = 0.5$, $T_1 = .5$, $T_2 = 2.5$ and $T_3 = 5.0$. The model identification scheme was also used for a 5-parameter model of Equation 2.17. The reason for choosing the model of Equation 2.17 is the general acceptance of this model in literature for human subjects.

$$G(j\omega) = \frac{Ke^{-\tau s}\,(1 + T_1 s)}{(1 + T_2 s)(1 + T_3 s)} \tag{2.17}$$

With parameters chosen as

$$\begin{aligned} K &= 2.0 \\ \tau &= 0.2 \text{ sec} \\ T_1 &= 0.2 \text{ sec} \\ T_2 &= 0.5 \text{ sec} \\ T_3 &= 5.0 \text{ sec} \end{aligned}$$

A typical set of parameters identified was

$$\begin{aligned} \tau &= 0.20012 \text{ sec} \\ K &= 1.9990 \\ T_1 &= 0.2005 \text{ sec} \\ T_2 &= 0.5008 \text{ sec} \\ T_3 &= 4.995 \text{ sec} \end{aligned}$$

with $s = 0.31970 \times 10^{-5}$. Several starting parameter vectors were chosen for both 4 parameter and 5 parameter models and results were comparable to those discussed above. A typical run with 6 trials took 60 seconds of computer time i.e., 10 seconds per trial.

Table 2.1 and 2.2 contain the initial and final vectors for 4-parameter and 5-parameter models respectively.

Table 2.1 - 4-Parameter Model

Run #	# of Iterations	Initial Vector	Final Vector	Correlation Error
1	119	τ = .5	τ = .2078	$.1964 \times 10^{-5}$
		T_1 = .5	T_1 = .211	
		T_2 = 2.5	T_2 = .5130	
		T_3 = 5.0	T_3 = 4.985	
2	131	τ = .45	τ = .1999	$.1935 \times 10^{-5}$
		T_1 = .6	T_1 = .1999	
		T_2 = 4.0	T_2 = .5000	
		T_3 = 5.0	T_3 = 4.9980	
3	83	τ = .3	τ = .1991	$.5527 \times 10^{-6}$
		T_1 = .3	T_1 = .1956	
		T_2 = .5	T_2 = .4143	
		T_3 = 5.2	T_3 = 5.008	

Table 2.2 - 5-Parameter Model

Run #	# of Iterations	Initial Vector	Final Vector	Correlation Error
1	140	$\tau = .5$	$\tau = .2001$	$.1349 \times 10^{-6}$
		$T_1 = .5$	$T_1 = .2005$	
		$T_2 = 2.5$	$T_2 = .5008$	
		$T_3 = 5.0$	$T_3 = 4.995$	
		$K = 1.0$	$K = 1.9999$	
2	104	$\tau = .3$	$\tau = .1998$	$.1445 \times 10^{-6}$
		$T_1 = .4$	$T_1 = .1994$	
		$T_2 = 2.0$	$T_2 = .4991$	
		$T_3 = 6.0$	$T_3 = 5.0041$	
		$K = 2.0$	$K = 2.0001$	
3	42	$\tau = .6$	$\tau = .2001$	$.1491 \times 10^{-6}$
		$T_1 = .6$	$T_1 = .2005$	
		$T_2 = 4.0$	$T_2 = .5009$	
		$T_3 = 6.0$	$T_3 = 4.9957$	
		$K = 2.0$	$K = 1.9989$	

F. MODELING RESULTS

In the investigation detailed here, three Rhesus monkeys, Butch, Hoppy and Big Boy were used as subhuman operators in a shock controlled compensatory tracking situation. For each of the animals, five tapes were randomly chosen, both in .15 Hz and .05 Hz ranges. One of the three monkeys, namely Big Boy, was trained for only a few days on 0.05 Hz. Consequently, the number of recordings made were not enough to estimate his describing function in the .05 Hz range.

The describing function data, namely magnitude in dB and phase angle in degrees, for the three primates, is presented in Tables M1 through M5. Tables M2, M3 and M4 contain estimates for frequency bandwidth of .15 Hz and Tables M1 and M5 for .05 Hz. The last two columns in each of the Tables M1-M5, both for magnitude and phase angle, contain the mean for the five sets of data together with the standard deviation. Both for the .15 Hz and 0.05 Hz signal bandwidths, magnitude of the describing function averaged between -12.0 dB and 30.0 dB whereas the phase angle averaged between 10° to -115°. In the frequency range of .15 Hz, the standard deviation in magnitude and phase angle were respectively of the order of 0-3 dB and 3°-30°. In the 0.05 Hz bandwidth, however, the deviation was relatively higher. This was mainly due to the aliasing introduced by the very low frequency components in the input signal. Mean describing function estimates together with the standard deviation are plotted in Figs. 2.9 through 2.13.

Similarly, Tables H1 and H2 contain the describing function data for human subjects Human 2 and Human 3 for both frequency ranges 0.05 Hz and 0.15 Hz. The magnitude and phase angle for the human subjects ranged from 5 dB to 45dB, and -10° to -110° respectively. It should

Table M1. Describing Function Data - Hoppy

Analog Signal Bandwidth - 0.05 HZ

MAGNITUDE IN DB

FREQ. (HZ)* 245.6	DAY 06/04/76	06/08/76	06/11/76	06/17/76	06/21/76	MEAN	STD. DEV.
1	17.77	13.41	17.40	29.02	18.43	19.21	5.21
3	17.48	12.83	14.21	14.24	14.58	14.67	1.53
5	12.62	13.34	8.21	12.01	16.85	12.61	2.77
7	19.77	19.42	8.22	20.73	17.85	17.20	4.58
9	11.03	14.14	4.47	12.38	12.88	10.98	3.41
11	10.22	10.47	13.13	11.10	11.73	11.33	1.04
13	10.51	9.77	1.38	11.68	12.28	9.12	3.97
15	8.43	7.64	-3.53	8.20	14.68	7.08	5.89
17	24.16	9.68	-7.79	6.27	6.79	7.82	10.13
19	12.64	7.98	0.85	5.84	3.17	6.09	4.06
21	0.53	3.17	-0.71	8.04	-0.85	2.04	3.33
23	6.30	3.46	-3.95	6.66	4.37	3.37	3.85
25	-1.25	-2.23	-8.05	2.23	6.32	-0.59	4.79
27	-3.85	-1.50	3.76	-1.06	0.94	-0.34	2.55
29	-5.91	-0.79	-4.65	-0.49	-4.25	-3.22	2.18

PHASE IN DEGREES

FREQ. (HZ)* 245.6	DAY 06/04/76	06/08/76	06/11/76	06/17/76	06/21/76	MEAN	STD. DEV.
1	-151.08	-118.47	-26.46	162.61	-118.64	-50.4	114.3
3	-2.94	-74.87	-72.39	-54.30	-35.65	-48.0	26.6
5	-35.18	-44.26	-69.43	-58.67	-60.93	-53.7	12.3
7	-36.16	-43.34	-77.25	-60.23	-48.96	-53.2	14.4
9	-66.12	-47.92	-89.59	-74.46	-45.03	-64.6	16.6
11	-60.90	-46.36	-79.21	-72.42	-60.34	-63.8	11.3
13	-66.26	-63.12	-95.91	-55.37	-31.68	-62.5	20.6
15	-63.70	-52.54	-83.19	-50.15	-88.14	-67.5	15.6
17	-37.98	-77.83	-28.84	-81.95	-98.00	-64.9	26.8
19	-100.63	-89.14	-109.65	-79.69	-65.82	-89.0	15.4
21	-89.44	-96.23	-103.20	-122.24	-114.36	-105.1	11.9
23	-118.55	-63.44	-79.27	-99.63	-71.00	-86.4	20.1
25	-141.79	-137.98	-34.92	-106.18	-134.14	-111.0	40.1
27	-90.40	-129.66	-98.96	-116.61	-74.62	-102.1	19.4
29	-59.50	-96.85	-66.53	-149.58	-97.14	-93.9	31.9

Table M2. Describing Function Data - Hoppy

Analog Signal Bandwidth - 0.15 Hz

MAGNITUDE IN DB

FREQ. (HZ)* 122.6	DAY 07/12/76	07/13/76	07/20/76	07/26/76	08/02/76	MEAN	STD. DEV.
1	28.02	22.46	14.53	23.27	42.60	26.18	9.29
3	13.16	20.66	17.41	18.41	15.38	17.31	2.56
5	16.70	16.30	12.78	16.37	17.73	15.99	1.69
7	12.00	14.71	12.46	15.39	13.61	13.63	1.29
9	13.21	14.00	10.80	11.04	11.99	12.21	1.23
11	10.83	13.90	13.91	9.05	10.58	11.65	1.94
13	10.90	9.90	12.44	8.80	9.26	10.25	1.30
15	6.09	9.16	11.72	7.68	8.69	8.57	1.85
17	14.83	7.24	10.19	7.24	7.73	9.45	2.91
19	9.83	7.98	10.02	6.88	7.34	8.41	1.29
21	10.89	9.63	8.85	7.93	7.32	8.73	1.21
23	8.52	6.84	6.29	7.44	9.95	7.81	1.30
25	6.79	5.72	9.32	4.14	5.32	6.46	1.73
27	6.99	4.83	4.95	3.18	1.31	4.25	1.90
29	3.40	0.55	3.76	3.69	1.38	2.55	1.33

PHASE IN DEGREES

FREQ. (HZ)* 122.6	DAY 07/12/76	07/13/76	07/20/76	07/26/76	08/02/76	MEAN	STD. DEV.
1	-75.68	-125.56	-14.26	-0.76	8.70	-41.7	51.4
3	-60.14	12.38	-32.19	-20.70	-58.38	-31.8	25.8
5	-55.81	-50.77	-22.45	-40.30	-71.81	-48.2	16.4
7	-55.73	-59.38	-36.50	-43.57	-31.03	-51.2	19.7
9	-82.69	-61.35	-55.47	-65.88	-35.32	-60.1	15.4
11	-64.34	-53.76	-41.86	-58.82	-53.80	-54.5	7.4
13	-66.11	-60.97	-48.22	-51.08	-50.97	-55.5	6.9
15	-74.81	-68.19	-38.57	-51.43	-48.76	-56.4	13.3
17	-61.81	-59.79	-51.93	-59.36	-55.64	-57.9	3.4
19	-73.44	-61.56	-54.60	-55.95	-62.91	-61.7	5.7
21	-91.97	-53.05	-64.16	-56.13	-65.99	-66.3	13.7
23	-74.60	-71.29	-79.16	-58.25	-56.90	-68.1	8.9
25	-73.65	-81.17	-73.39	-75.64	-79.39	-76.7	3.1
27	-75.32	-74.14	-92.94	-85.57	-64.71	-78.5	9.9
29	-82.53	-74.54	-95.88	-105.91	-63.37	-85.4	13.9

Table M3. Describing Function Data - Butch

Analog Signal Bandwidth - 0.15 Hz

MAGNITUDE IN DB

FREQ. (HZ)* 122.6	DAY 07/07/76	07/20/76	07/23/76	08/02/76	08/03/76	MEAN	STD. DEV.
1	19.45	23.13	24.64	29.88	12.26	21.87	5.86
3	22.35	19.10	21.84	24.30	13.76	20.27	3.65
5	18.79	17.10	17.41	22.64	11.41	17.47	3.62
7	19.30	16.62	15.33	18.36	10.99	16.12	2.91
9	16.54	15.71	18.11	16.49	10.82	15.53	2.48
11	13.34	14.95	17.97	16.85	10.71	14.76	2.59
13	11.86	15.94	16.15	17.15	10.84	14.39	2.53
15	15.52	14.28	15.97	13.82	12.54	14.43	1.23
17	10.45	12.33	12.49	12.68	8.44	11.30	1.63
19	8.79	9.99	12.60	12.83	7.33	10.31	2.14
21	8.62	9.63	12.13	9.29	6.31	9.20	1.87
23	8.59	8.94	8.21	8.02	7.87	8.33	0.39
25	9.52	8.10	10.52	9.99	5.99	8.82	1.63
27	3.96	6.99	7.59	5.12	6.55	6.04	1.32
29	4.25	5.40	4.49	6.72	3.40	4.85	1.13

PHASE IN DEGREES

FREQ. (HZ)* 122.6	DAY 07/07/76	07/20/76	07/23/76	08/02/76	08/03/76	MEAN	STD. DEV.
1	-65.54	-10.58	-102.02	-160.19	-60.71	-79.8	49.6
3	-9.55	-40.34	-25.20	-32.25	-67.50	-35.0	19.2
5	-42.38	-26.38	-2.38	-8.31	-70.03	-29.9	24.5
7	-58.15	-37.18	-49.48	-29.18	-63.94	-47.6	12.9
9	-50.47	-33.38	-44.61	-40.50	-53.78	-44.5	7.2
11	-55.76	-50.38	-27.75	-52.92	-55.01	-48.4	10.5
13	-75.92	-52.84	-56.14	-53.82	-59.70	-59.7	8.5
15	-67.77	-56.08	-68.54	-52.12	-52.61	-59.4	7.3
17	-69.38	-71.39	-63.09	-76.53	-40.39	-64.1	12.4
19	-80.35	-58.13	-71.33	-82.73	-64.93	-73.5	6.9
21	-84.64	-57.00	-78.88	-87.94	-59.10	-73.5	13.0
23	-80.68	-64.61	-85.23	-76.96	-58.33	-75.2	7.7
25	-79.50	-67.47	-74.95	-95.61	-77.53	-79.0	9.2
27	-78.88	-58.17	-94.66	-91.50	-77.95	-82.2	9.7
29	-87.01	-73.56	-95.90	-81.77	-82.35	-84.2	7.3

Table M4. Describing Function Data - Big Boy

Analog Signal Bandwidth - 0.15 Hz

MAGNITUDE IN DB

FREQ. (HZ)* 122.6	DAY 07/20/76	07/23/76	07/26/76	08/04/76	08/05/76	MEAN	STD. DEV.
1	6.88	-0.34	-6.83	0.86	5.93	1.30	4.93
3	11.58	-7.52	5.27	21.22	7.23	7.56	9.33
5	6.43	4.48	2.86	6.42	9.11	5.86	2.10
7	-1.70	1.97	3.41	9.77	6.77	4.04	3.95
9	0.29	8.75	3.41	0.67	3.74	3.37	3.03
11	-11.31	5.98	14.67	10.58	8.29	5.64	8.95
13	-1.28	5.82	15.45	7.28	2.93	6.04	5.54
15	-8.78	16.89	6.70	1.16	-0.71	3.05	8.52
17	-5.68	-0.26	-4.59	-1.71	2.32	-1.98	2.90
19	-7.87	-9.35	-2.56	-5.17	-1.21	-5.23	3.07
21	-10.62	6.82	-0.07	-1.47	3.47	-0.37	5.88
23	-26.51	1.49	-0.91	-2.36	1.29	-5.40	10.65
25	-11.76	-5.10	-10.04	-7.48	-5.64	-8.00	2.55
27	-9.34	-3.67	-1.71	-8.56	0.59	-4.54	3.86
29	-11.61	-11.23	-11.16	-16.74	-13.08	-12.76	2.10

PHASE IN DEGREES

FREQ. (HZ)* 122.6	DAY 07/20/76	07/23/76	07/26/76	08/04/76	08/05/76	MEAN	STD. DEV.
1	-110.29	-158.53	162.33	-115.00	-116.92	-67.7	116.3
3	-107.20	-166.34	-97.82	-84.75	-54.80	-102.2	36.6
5	-52.23	-168.47	-88.87	-48.84	-11.29	-73.9	53.3
7	-86.75	-120.21	-88.52	-80.34	-125.42	-100.2	18.7
9	-115.71	-110.87	-57.41	-159.57	-88.08	-106.3	33.7
11	-103.42	-66.31	-132.54	-146.81	-34.87	-96.8	41.4
13	-87.81	-51.08	-26.22	-151.70	-46.53	-72.7	44.2
15	-39.49	-5.55	-110.56	-75.97	-82.71	-62.9	36.5
17	-34.11	-58.65	-87.42	-50.23	-114.43	-69.0	28.6
19	166.17	88.02	-79.54	-53.29	-62.21	11.8	97.7
21	-142.19	-80.51	-121.37	-74.19	-59.53	-95.6	31.1
23	-164.89	-110.43	-142.29	-93.25	-67.97	-115.8	34.5
25	-147.62	-64.56	-165.26	-76.56	-80.38	-106.9	41.2
27	-112.09	-117.91	-178.06	-82.73	-159.07	-130.0	34.2
29	109.85	-66.31	-159.15	-98.15	97.79	-23.2	108.0

Table M5. Describing Function Data - Butch

Analog Signal Bandwidth - 0.05 Hz

MAGNITUDE IN DB

FREQ. (HZ)* 245.6	DAY 06/07/76	06/11/76	06/16/76	06/22/76	06/30/76	MEAN	STD. DEV.
1	29.71	33.45	25.47	24.81	-21.43	20.20	21.14
3	17.14	32.60	24.58	17.53	-21.22	14.38	18.63
5	17.44	16.06	22.92	18.28	-19.11	11.12	15.29
7	20.54	12.80	19.12	18.90	-20.03	10.27	15.38
9	17.84	16.07	17.49	15.19	-16.20	10.08	12.17
11	15.40	8.55	15.34	12.86	-13.29	7.97	10.97
13	15.51	9.78	14.50	13.04	-8.05	9.02	8.76
15	11.70	13.16	20.68	10.53	-17.26	7.76	13.00
17	14.64	6.22	11.76	12.58	-9.71	7.10	8.86
19	14.00	7.76	10.68	7.64	-5.72	6.27	7.95
21	6.05	7.41	8.51	6.14	-14.10	2.80	8.50
23	3.89	4.40	11.96	4.81	-13.57	2.30	9.47
25	6.23	3.40	1.95	10.66	-12.87	1.87	7.95
27	7.02	-0.19	0.44	0.50	-13.13	-1.07	6.58
29	0.17	-3.10	2.11	1.53	-16.08	-3.07	6.75

PHASE IN DEGREES

FREQ. (HZ)* 245.6	DAY 06/07/76	06/11/76	06/16/76	06/22/76	06/30/76	MEAN	STD. DEV.
1	-16.15	-64.51	-176.83	-177.23	-57.97	-98.5	66.2
3	-16.21	-37.64	-60.80	-33.17	58.47	-19.1	41.3
5	-4.63	-82.51	-66.42	-26.97	-116.14	-59.3	39.6
7	-41.80	-55.64	25.53	-56.30	-17.53	-29.1	30.7
9	-34.19	-83.15	-3.90	-36.95	90.40	-13.6	57.5
11	-77.12	-128.87	-75.73	-65.33	51.83	-59.0	59.7
13	-76.69	-105.67	-69.81	-77.94	-179.20	-101.9	40.6
15	-60.07	-59.79	-37.97	-83.57	-40.53	-62.4	21.3
17	-74.75	-121.07	-60.48	-59.65	32.85	-56.6	50.0
19	-64.98	-115.77	-77.39	-75.33	33.08	-60.1	47.7
21	-62.27	-98.45	-87.52	-65.24	61.06	-51.1	57.6
23	-94.36	-130.22	-141.10	-96.62	19.67	-85.5	57.1
25	-124.97	-110.21	-106.68	-117.55	28.83	-86.1	57.8
27	-127.53	-92.41	-87.82	-91.93	18.42	-76.3	49.5
29	-83.77	-76.84	-92.19	-80.00	-3.59	-67.3	32.3

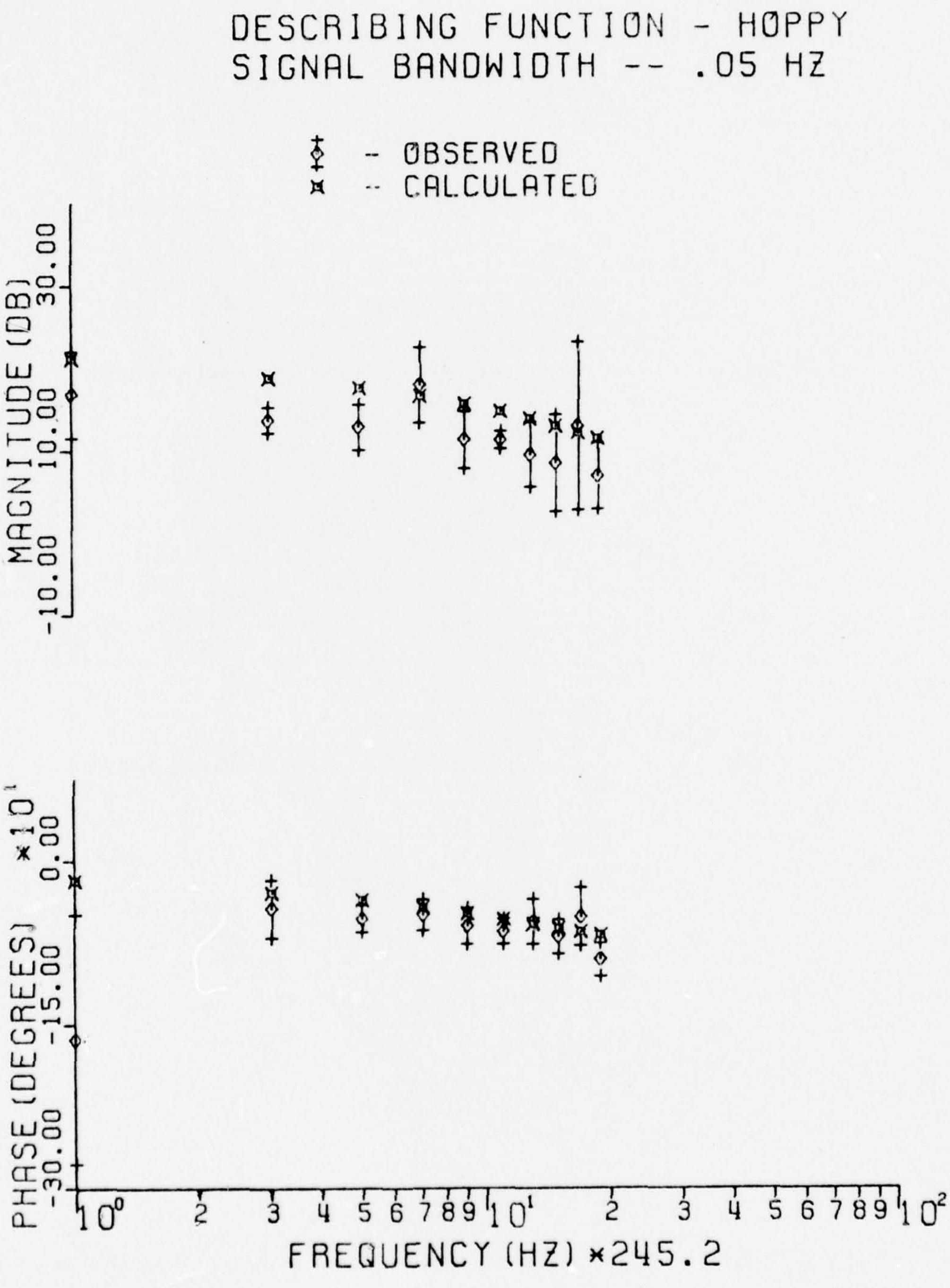
DESCRIBING FUNCTION - HOPPY
SIGNAL BANDWIDTH -- .05 HZ
- OBSERVED
-- CALCULATED
MAGNITUDE (DB)
-10.00
10.00
30.00
PHASE (DEGREES)
$\times 10^1$
-30.00
-15.00
0.00
10^0
2
3
4
5
6
7
8
9
10^1
10^2
FREQUENCY (HZ) $\times 245.2$

Fig. 2.9

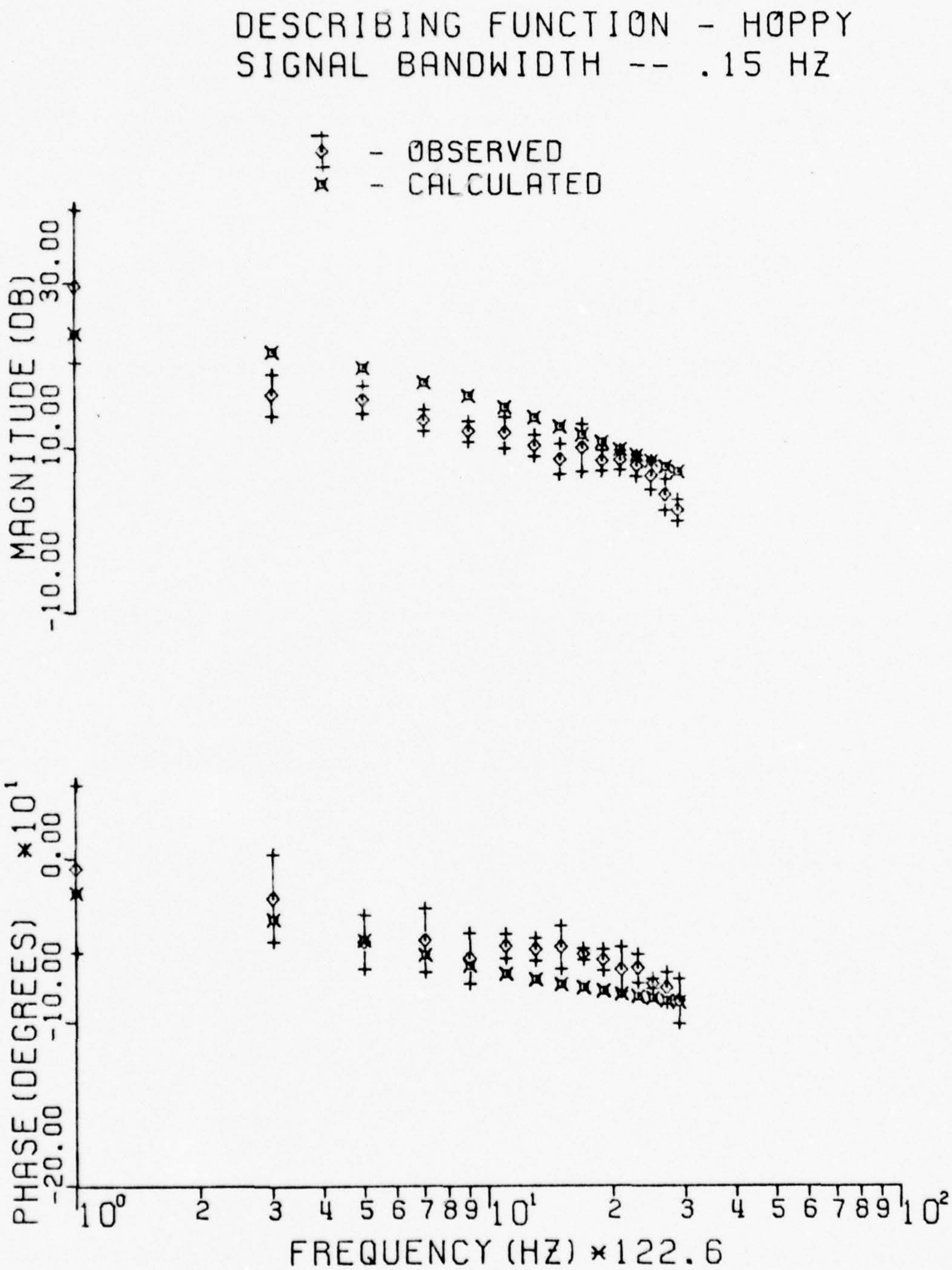
DESCRIBING FUNCTION - HOPPY
SIGNAL BANDWIDTH -- .15 HZ
- OBSERVED
- CALCULATED
MAGNITUDE (DB)
30.00
10.00
-10.00
PHASE (DEGREES) ×10¹
0.00
-10.00
-20.00
10⁰
2
3
4
5
6
7
8
9
10¹
10²
FREQUENCY (HZ) ×122.6

Fig. 2.10

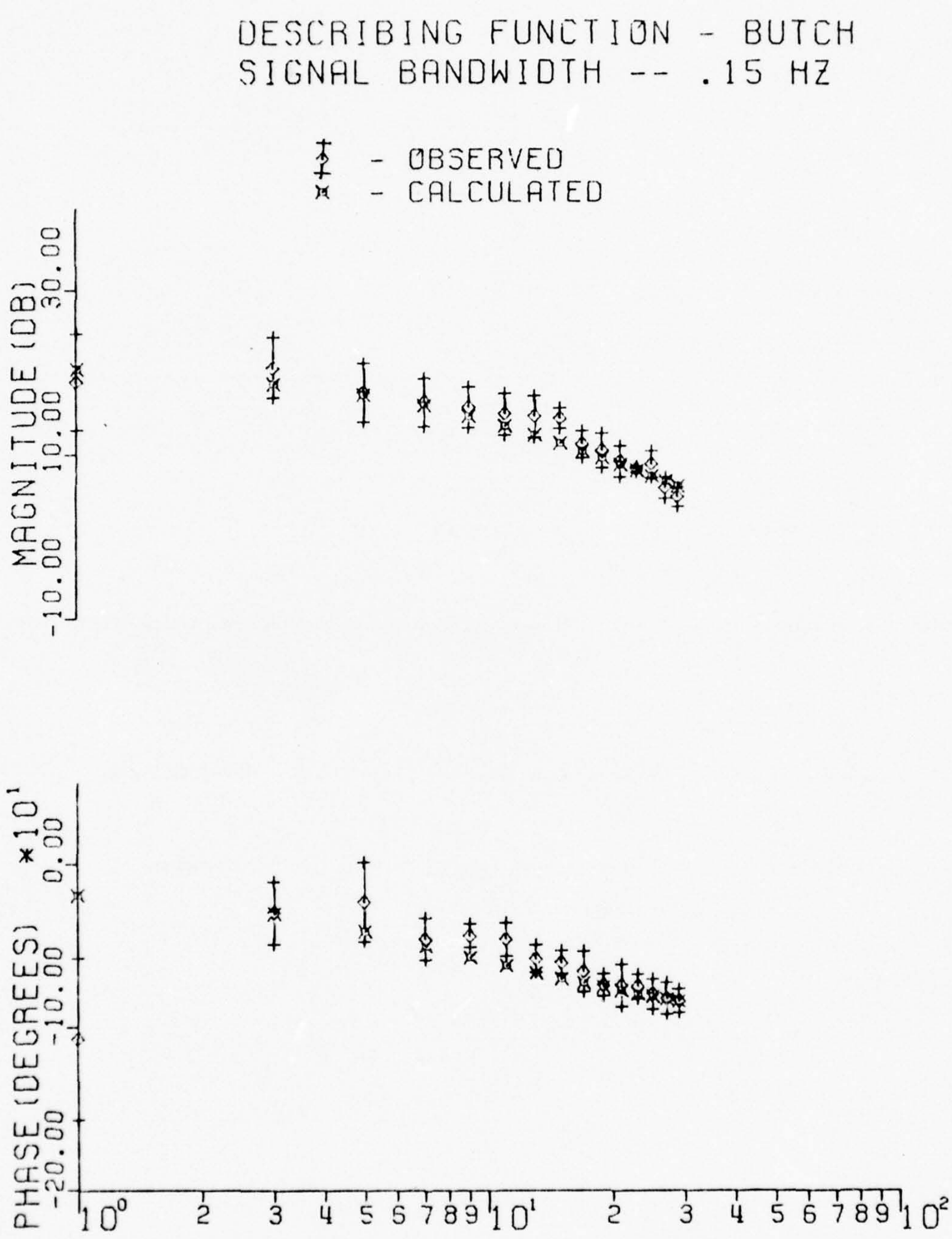
DESCRIBING FUNCTION - BUTCH
SIGNAL BANDWIDTH -- .15 HZ
- OBSERVED
- CALCULATED
MAGNITUDE (DB)
-10.00
10.00
30.00
PHASE (DEGREES) *10¹
-20.00
-10.00
0.00
10⁰
2
3
4
5
6
7
8
9
10¹
2
3
4
5
6
7
8
9
10²
FREQUENCY (HZ) *122.6

Fig. 2.11

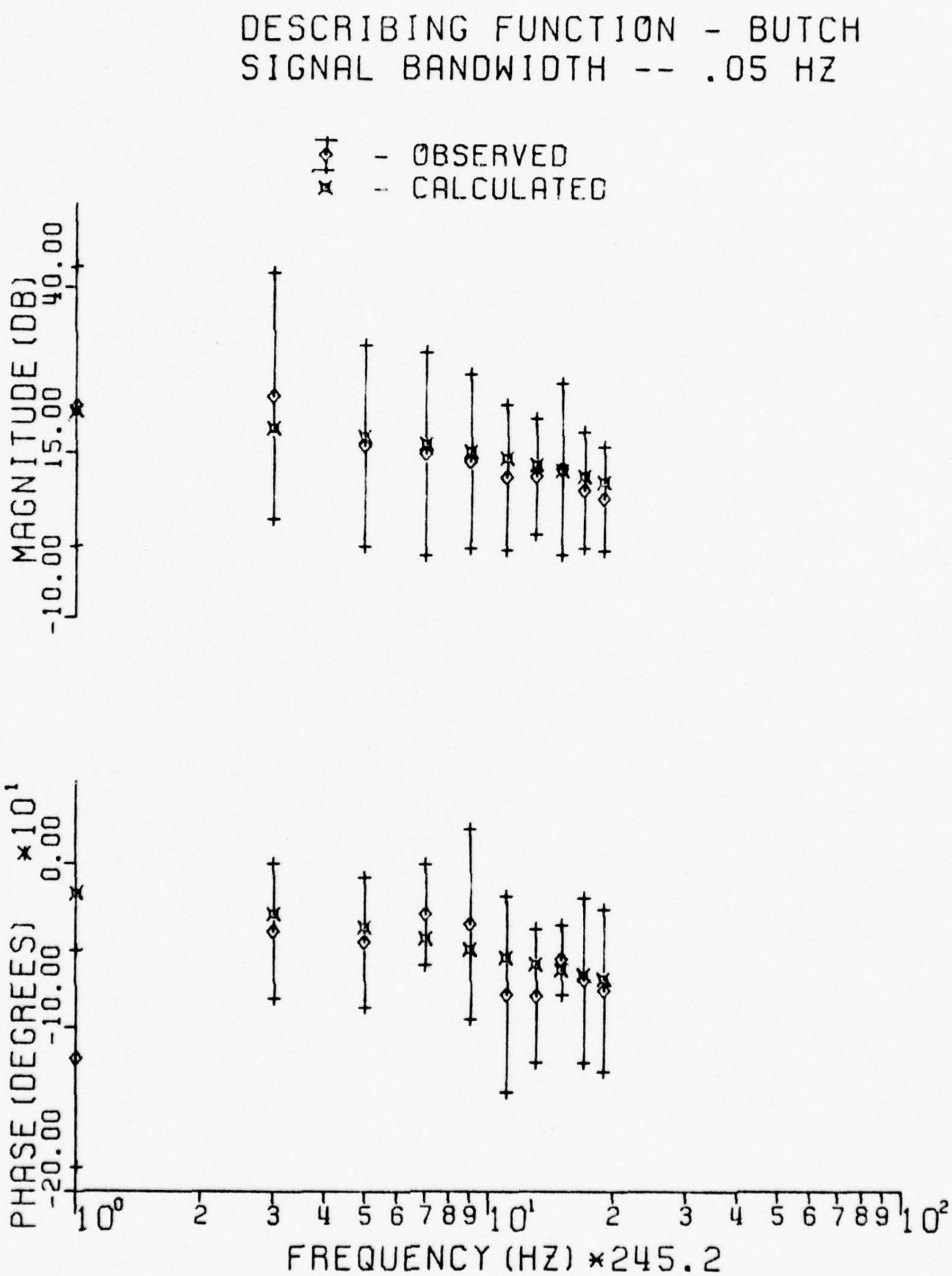
DESCRIBING FUNCTION - BUTCH
SIGNAL BANDWIDTH -- .05 HZ
- OBSERVED
- CALCULATED
MAGNITUDE (DB)
40.00
15.00
-10.00
PHASE (DEGREES) ×10¹
0.00
-10.00
-20.00
10⁰
2
3
4
5
6
7
8
9
10¹
10²
FREQUENCY (HZ) ×245.2

Fig. 2.12

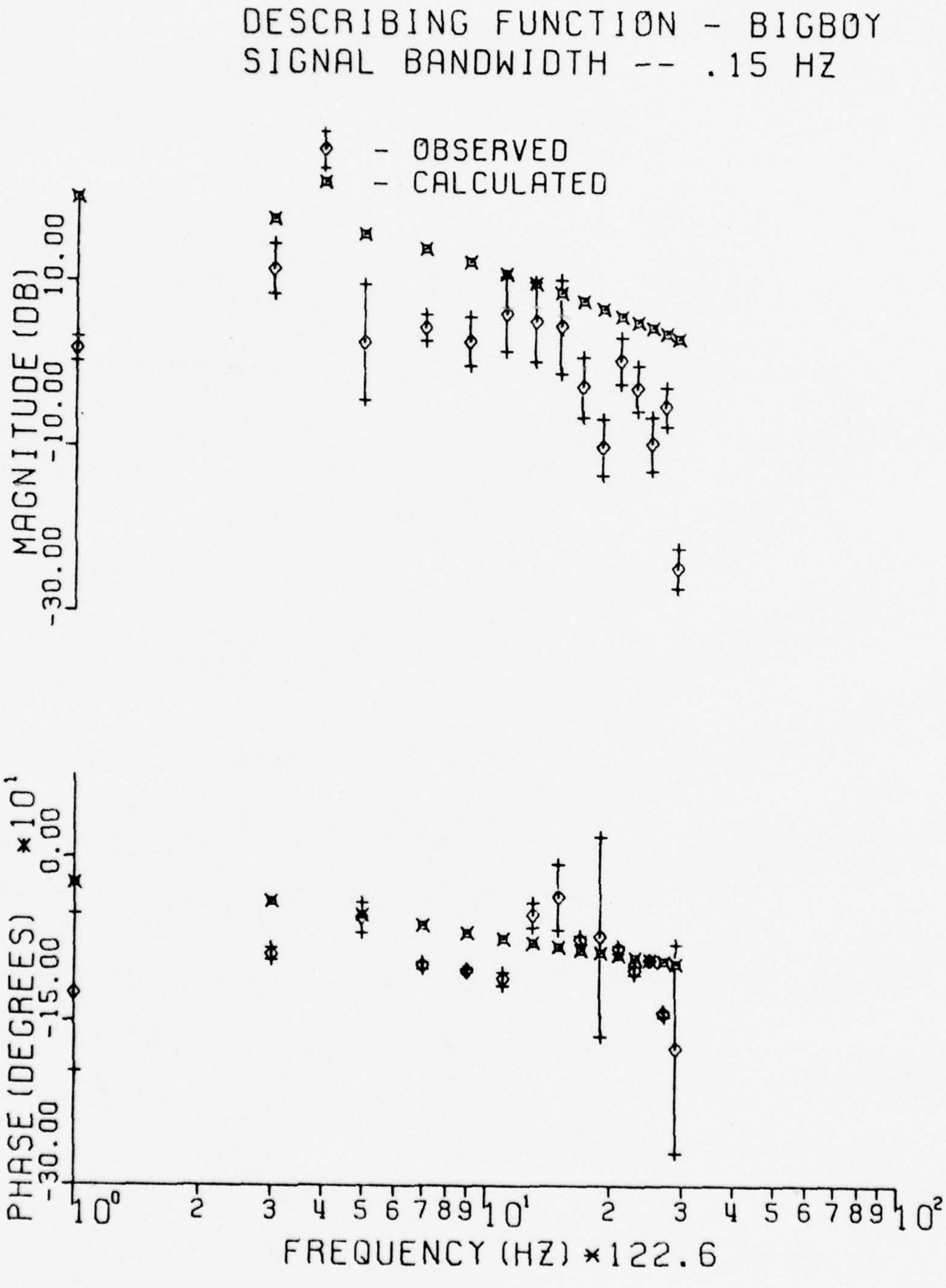
DESCRIBING FUNCTION - BIGBOY
SIGNAL BANDWIDTH -- .15 HZ
- OBSERVED
- CALCULATED
MAGNITUDE (DB)
10.00
-10.00
-30.00
PHASE (DEGREES) ×10¹
0.00
-15.00
-30.00
10⁰ 2 3 4 5 6 7 8 9 10¹ 2 3 4 5 6 7 8 9 10²
FREQUENCY (HZ) ×122.6

Fig. 2.13

Table H 1 - Describing Function Data - Human Subjects

Frequency Range: 0.15 Hz

Freq. (Hz) * 245.6	Subject - H 3 Mag. (dB)	Subject - H 3 Phase (Degrees)	Subject - H 2 Mag. (dB)	Subject - H 2 Phase (Degrees)
1	27.19	-62.25	23.13	-10.57
3	21.95	-62.39	19.10	-40.38
5	21.57	-56.48	17.10	-26.38
7	19.52	-57.07	16.61	-37.18
9	18.96	-77.68	15.70	-33.38
11	15.45	-81.07	14.95	-50.38
13	15.58	-77.76	15.94	-52.83
15	14.05	-76.85	14.27	-56.08
17	12.19	-77.49	12.38	-71.38
19	11.50	-68.77	9.98	-63.13

Table H 2 - Describing Function Data - Human Subjects

Frequency Range: 0.05 Hz

	Subject - H 2		Subject - H 3	
Freq. (Hz) * 122.6	Mag. (dB)	Phase (Degrees)	Mag. (dB)	Phase (Degrees)
1	34.68	-105.39	45.18	-59.07
3	30.31	-64.19	23.27	-48.48
5	21.93	-85.27	19.37	-57.19
7	23.72	-108.01	17.38	-77.14
9	23.97	-45.17	19.15	-63.91
11	23.82	-85.42	18.46	-29.22
13	19.63	-94.78	16.56	-89.22
15	18.46	-71.19	16.87	-73.30
17	15.32	-88.78	14.46	-69.00
19	12.84	-108.24	10.40	-88.32

be noted that the data presented for the human subjects is only for one run each. A mention must also be made of the fact that even though the task set for human subjects was compensatory in nature, it was similar, but not the same, as that set for the primates. Whereas the primates were punished with shock for their off target performances, the human subjects were punished for these errors on an error-cost basis which subtracted from the total amount of money ($3.00 maximum) which they could earn. Since data for the human operators were only recorded for one session, no statistical analysis was performed. The data for these subjects is plotted in Figs. 2.14-2.17. For the 0.05 Hz range, both for human and subhuman operators, ten describing function estimates were calculated starting at the fundamental frequency of (1/245.2) Hz and repeated for 9 frequency points, separated in frequency domain by (2/245.2) Hz. Similarly, for the 0.15 Hz range, the describing function estimates were computed for the fundamental frequency of (1/122.6) Hz and repeated at 14 frequency points equally spaced at (2/122.6) Hz.

Using the model identification scheme discussed earlier, model parameters for all subjects were calculated and are reported in Table P for both frequency ranges, .05 Hz and .15 Hz. The transfer functions corresponding to these model parameters are plotted in Figs. 2.9-2.17, along with the measured describing function.

It is apparent from Tables M2 and M3 that the describing functions measured for Butch and Hoppy over the .15 Hz range, were consistent from day to day. Also Figs. 2.9 and 2.10 show that performances of Hoppy and Butch were similar over the .15 Hz bandwidth. Table M4 shows marked variations in Big Boy's performance from one day to another. This inconsistenty in his tracking performance is also confirmed by his low

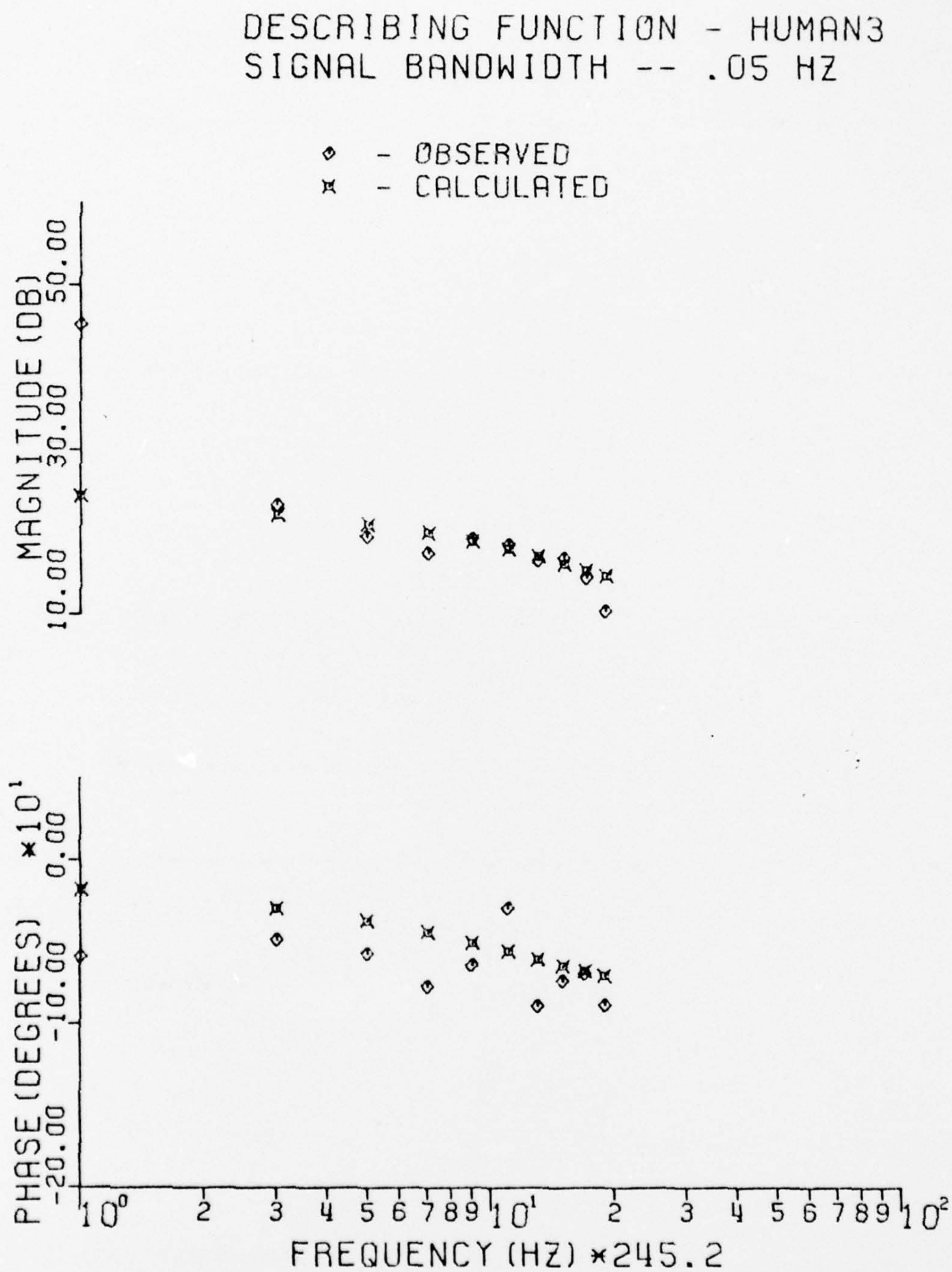
DESCRIBING FUNCTION - HUMAN3
SIGNAL BANDWIDTH -- .05 HZ
- OBSERVED
- CALCULATED
MAGNITUDE (DB)
10.00
30.00
50.00
PHASE (DEGREES) *10^1
-20.00
-10.00
0.00
10^0 2 3 4 5 6 7 8 9 10^1 2 3 4 5 6 7 8 9 10^2
FREQUENCY (HZ) *245.2

Fig. 2.14

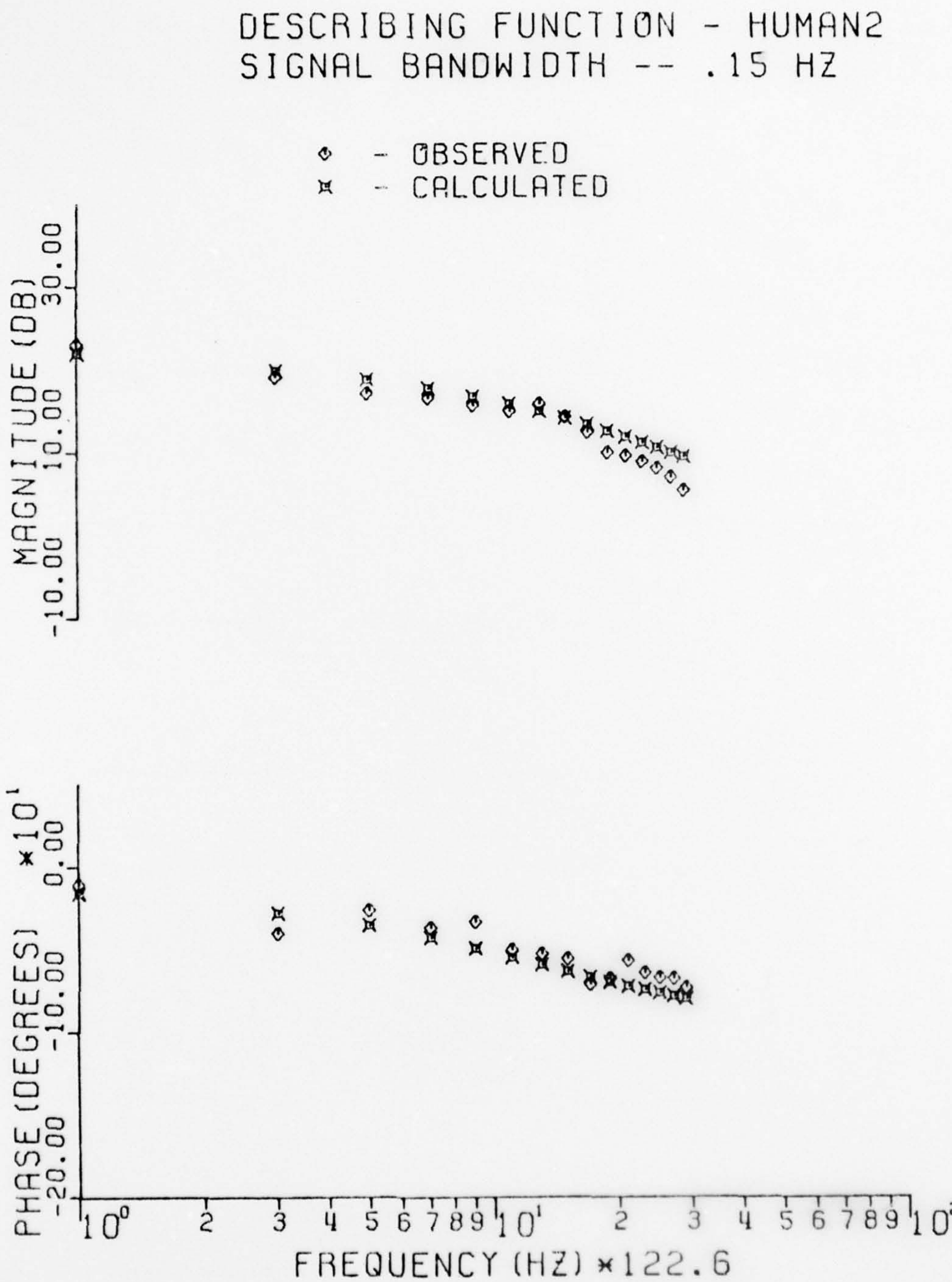
DESCRIBING FUNCTION - HUMAN2
SIGNAL BANDWIDTH -- .15 HZ
- OBSERVED
- CALCULATED
MAGNITUDE (DB)
30.00
10.00
-10.00
PHASE (DEGREES) ×10¹
0.00
-10.00
-20.00
10⁰
2
3
4
5
6
7
8
9
10¹
2
3
4
5
6
7
8
9
10²
FREQUENCY (HZ) ×122.6

Fig. 2.15

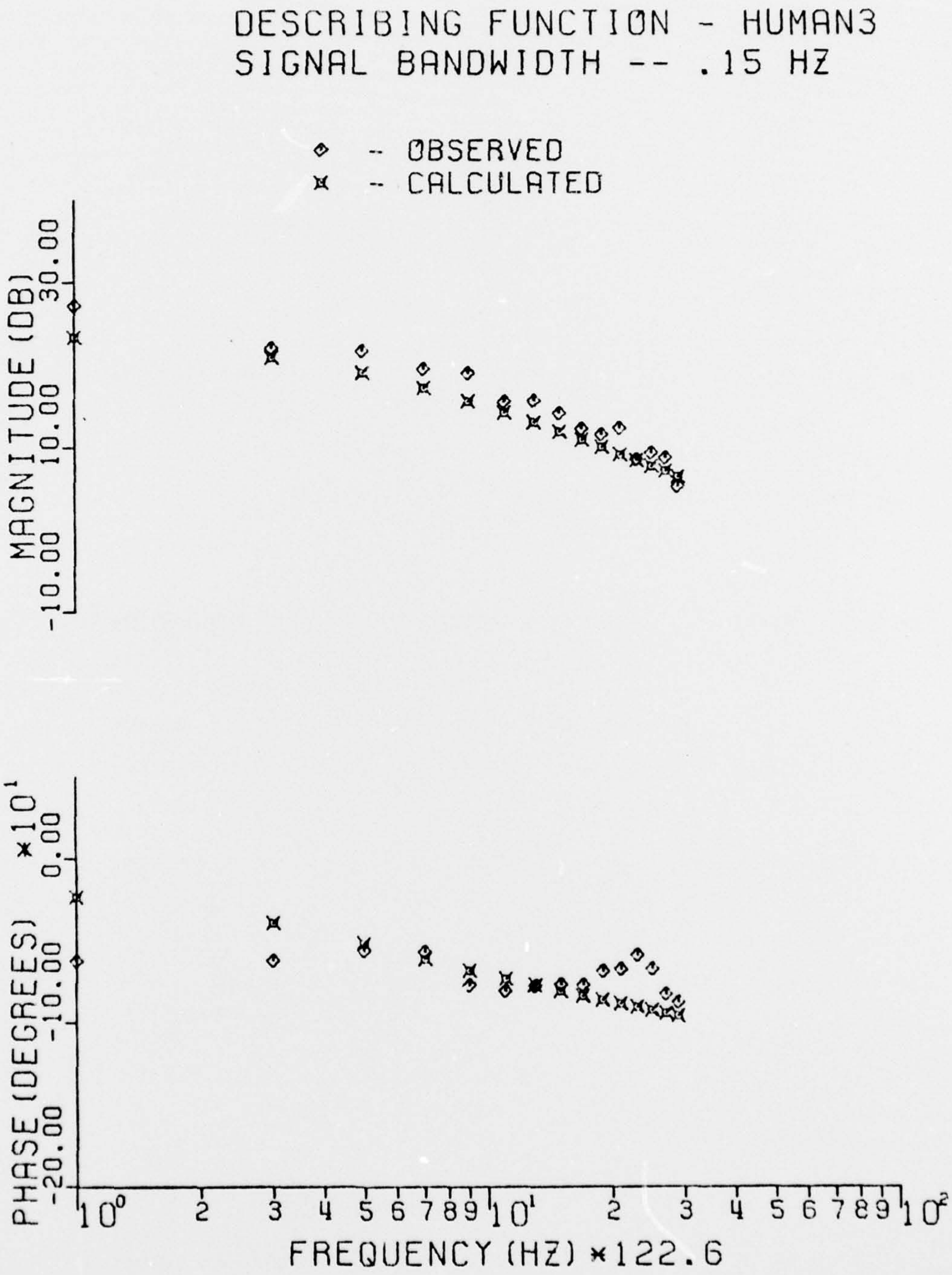
DESCRIBING FUNCTION - HUMAN3
SIGNAL BANDWIDTH -- .15 HZ
◇ - OBSERVED
⌘ - CALCULATED
MAGNITUDE (DB)
30.00
10.00
-10.00
PHASE (DEGREES) ×10¹
0.00
-10.00
-20.00
10⁰
2
3
4
5 6 7 8 9
10¹
2
3
4
5 6 7 8 9
10²
FREQUENCY (HZ) ×122.6

Fig. 2.16

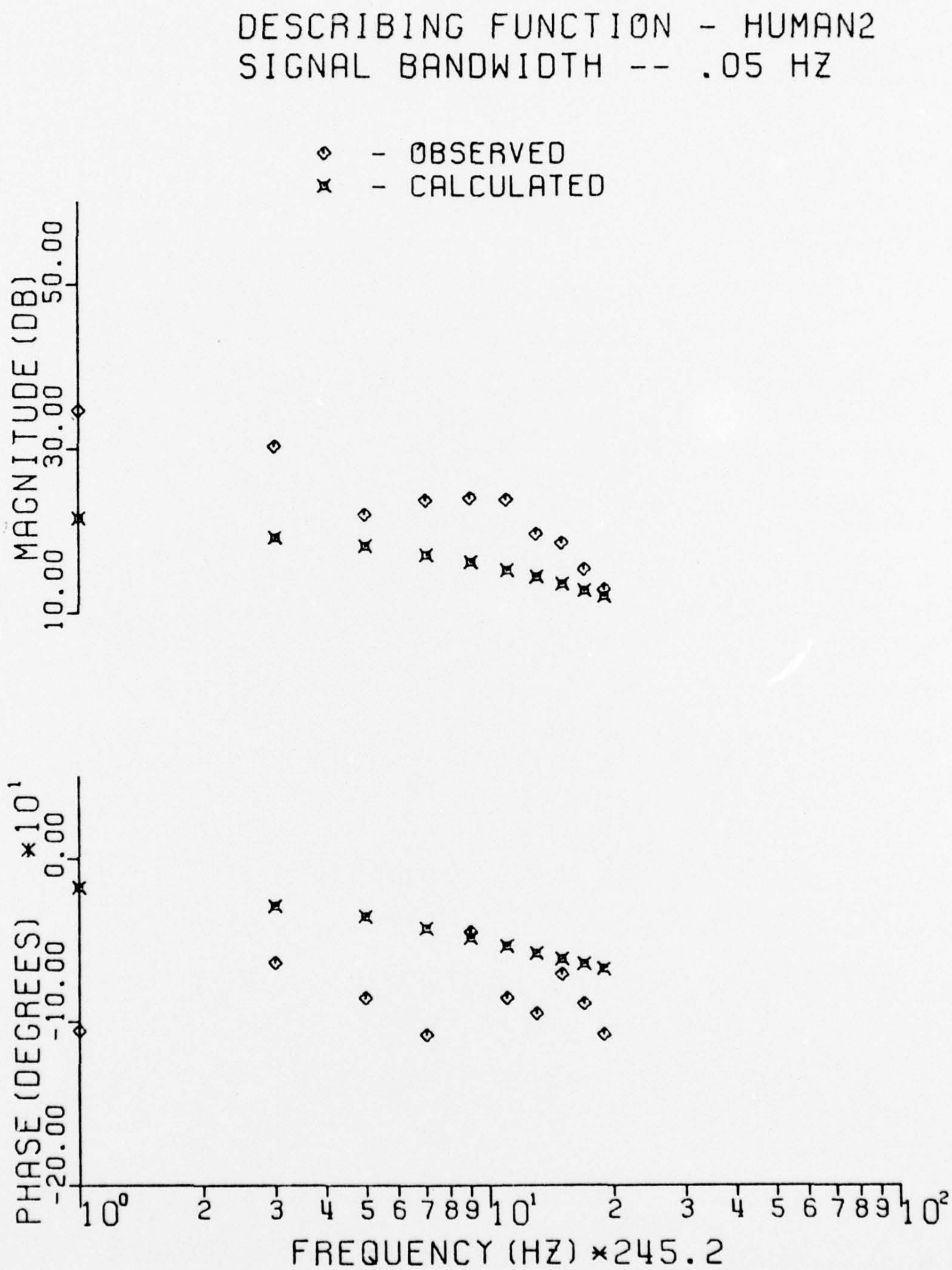
DESCRIBING FUNCTION - HUMAN2
SIGNAL BANDWIDTH -- .05 HZ
◇ - OBSERVED
⌘ - CALCULATED
MAGNITUDE (DB)
10.00
30.00
50.00
PHASE (DEGREES) *10[1]
-20.00
-10.00
0.00
10[0] 2 3 4 5 6 7 8 9 10[1] 2 3 4 5 6 7 8 9 10[2]
FREQUENCY (HZ) *245.2

Fig. 2.17

correlation index $\overline{\rho^2}(\omega)$ tabulated in Tables R1 and R2 respectively. The $\overline{\rho^2}(\omega)$, from a control's viewpoint, is a measure of the linearity in the operator's response. Alternatively, $[1 - \rho^2(\omega)]$ is a measure of the "remnant" present in the operator's response. A close look at Tables R1 and R2 reveals consistently high values of ρ^2 for Hoppy and Butch over both ranges of frequency used. The values typically lie between 0.58 and .96. The animals showed a marked tendency to introduce more remnant at higher frequencies. The human subjects' responses were much more linear over the frequency spectrum used, as confirmed by high $\rho^2(\omega)$ values.

The observed inconsistency in Big Boy's response can, in part, be explained in terms of adaptation and motivation. Again, referring to the Remnant column in Table P it may be noticed that the reported values, which physically represent minimized sum-squared-error S, are quite consistent for all subjects except Big Boy. The least-squared error calculated was seemingly low and inconsistent with $\rho^2(\omega)$ values. This was possible due to a local minima observed in his unpredictable response. The interanimal consistency as seen in Hoppy's and Butch's performance could be attributed to their ability to adapt to the tracking task. Adaptation together with motivation produced the same functional relationships regardless of the species. In the case of Big Boy, motivation seems to have been more influential, for, even though he was given the same shock treatment every day, his performance was inconsistent and showed large variations. In the .05 Hz range Hoppy showed relatively less variation than Butch.

The data for human subjects plotted in Figs. 2.14-2.17 show similarity of trend with that of Rhesus monkeys. As seen from Figs. 2.9-2.17

the modeled transfer functions, very closely match the measured describing function both for human and subhuman operators except Big Boy.

The mathematized and quantitative observations discussed above show qualitative agreement with preliminary observations made on the basis of digital, Time-On-Target scores (TOT). The following table shows percent time on target for all subjects.

COMPENSATORY TASK

Time-On-Target (TOT)

Frequencies	Humans	Monkeys
0.05 Hz	99.5	94.7
	98.9	99.0
0.15 Hz	99.3	94.2
	98.5	98.2
		90.8

DISCUSSION

1. Input Signals

Before discussing the experimental describing functions and the calculated transfer functions from estimated model parameters, it is appropriate to examine the nature of the time signals circulating in the operator/machine loop. The overall system inputs were derived from a *Gaussian noise generator and the* operator attempted to force the system output to equal the system input by operating on the stick controller. Depending on the set performance criteria, operator's output may or may not have been Gaussian. To have a better insight into this aspect of the problem, the width of the window will have to be taken into account

(see Window Width). However, since the input signal x(t) was an externally generated random noise, it would be uncorrelated with any noise generated within the system and present at the output. This precisely means that the correlation index $\rho^2(\omega)$ given by

$$\rho^2(\omega) = \frac{|\Phi_{xy}(\omega)|^2}{\Phi_{xx}(\omega)\,\Phi_{yy}(\omega)} \qquad 2.18$$

would be a true measure of the nonlinearity in the operator response.

Apart from being Gaussian-random, the noise bandwidth was set to a maximum cutoff frequency of .15 Hz. This extremely low frequency range was primarily used for two reasons: first, to train the animals on a simple task and then gradually make the task more difficult. The second reason was to provide a data base in a frequency range that has hitherto been uninvestigated. Further, it was observed that at higher frequency ranges, the animals would not track despite the shock treatment.

2. Window-width

The error signal e(t) was generated by taking the difference of y(t) and x(t). This would have been mathematically appropriate if the subjects were required to align the cursor with a central line on the CRT display. In such a situation a leftward movement of the cursor would have required rightward compensation and vice-versa. Since this task would have been extremely difficult, the subjects were required to align the cursor with a line of finite width (one inch). From a control's standpoint this changed the nature of the task. Quantitatively, the error signal e(t) could always have been non-zero even though the subject was tracking 99% of the time. In principle, the animal was not given a true indication of the error signal. Consideration must also

be given to the fact that the animal could have just been sitting and wiggling the stick generating error even though his TOT scores indicated zero or no error. Conclusively then, simplification in task resulted in ambiguities in operator performance. This is confirmed by Big Boy's performance results. His TOT scores were appreciably high (90.0%) even though the correlation index reflected a very poor performance (.30).

3. Human vs. Subhuman Operators.

As part of the research, data were collected on human and subhuman subjects both in compensatory and pursuit tracking situations. However, in the case of pursuit, since only discrete input frequencies (.122 Hz and .163 Hz) were used, describing function data was not calculated. Therefore, comparisons between the two species will be made solely on the basis of results obtained from the compensatory tracking task. In this context, it is of interest that studies reported by Bachman et al. (1976) focused on the issue of man-monkey comparisons in a tracking situation. They used a primate-training task quite similar to that discovered in our laboratory a few years ago. Bachman et al. have reported results, similar to those observed in this investigation, which lend credibility to monkey-man extrapolation. Bachman et al. observed very low "remnant" in monkey response which is essentially what is reported in Tables R1 and R2.

Quantitative evaluation of man-monkey performance revealed that for both the human and subhuman operators the transportation lag was within .08-.19 seconds. This is comparable with transportation delay reported in literature for human operators in similar tracking situations, Shinners (1974), McRuer et al. (1974) and Bachman et al. (1976).

Table R 1 - Correlation Index - $\rho^2(\omega)$

Frequency Bandwidth - 0.15 Hz

Freq. (Hz) * 122.58	Monkeys			Human Subjects	
	Big Boy	Butch	Hoppy	H 2	H 3
1	.23	.92	.89	.99	.99
3	.28	.94	.94	.99	.98
5	.40	.94	.93	.98	.98
7	.27	.95	.93	.99	.98
9	.45	.96	.94	.99	.98
11	.32	.95	.93	.99	.98
13	.35	.95	.89	.98	.98
15	.24	.95	.92	.99	.90
17	.23	.95	.90	.98	.98
19	.19	.94	.93	.99	.99
21	.25	.93	.90	.98	.97
23	.22	.89	.83	.98	.96
25	.20	.86	.80	.92	.85
27	.16	.80	.76	.88	.82
29	.14	.79	.68	.89	.88

Table R 2 - Correlation Index - $\rho^2(\omega)$

Frequency Bandwidth - 0.05 Hz

Freq. (Hz) * 245.2	Monkeys: Butch	Monkeys: Hoppy	Human Subjects: H 2	Human Subjects: H 3
1	.77	.91	.98	.99
3	.78	.94	.98	.99
5	.77	.94	.99	.99
7	.77	.82	.98	.98
9	.78	.82	.98	.99
11	.76	.82	.98	.99
13	.79	.87	.97	.97
15	.76	.81	.97	.97
17	.81	.66	.91	.97
19	.87	.58	.91	.95

The results obtained in this investigative study along with those of Bachman et al. offer strong convincing evidence for the contention that both these species show similar performances. Therefore, the fundamental differences between man and monkey reported by some do not match empirical results obtained in this study. Further examination of this will require further experimentation and more complex tracking tasks.

4. Comparison with Data in the Literature.

To this author's knowledge, this kind of research using primate operators has only been reported by Bachman et al. (1976). This research was partly conducted to add to the rather meager data base of primate tracking experiments. The table below shows "best fit" parameters reported by Bachman et al.

Table L - Data from Bachman et al.

Parameter	Subj. H 1	Subj. H 2	Subj. M 1	Subj. M 2
K, Gain	20.0	11.0	7.5	8.0
T_L, Lead	4.2	1.4	4.2	1.6
T_N, Lag	41.9	31.4	20.9	20.9
T_I, Lag	1.6	0.3	2.1	0.5
τ, Time Delay	0.14	0.21	0.14	0.19

Even though the results of the reported study (see Table P) reflect remarkable similarity with the observations made by the above authors, considerable care must be exercised in interpreting the results. Results of Table P show less variation than those in Table L above. This

Table P - Model Parameters

Freq. Range (Hz)	Subject Name	τ (sec)	T_1 (sec)	T_2 (sec)	T_3 (sec)	K	Remnant
0.05	H 2	.16	18.01	28.99	3.99	18.97	418.2
	H 3	.16	18.00	28.99	3.99	18.77	288.3
	Butch	.09	18.01	28.99	4.59	13.00	398.4
	Hoppy	.09	18.01	28.88	3.99	13.00	365.0
0.15	H 2	.09	18.00	28.99	3.91	13.70	22.9
	H 3	.17	18.00	27.10	3.98	18.98	276.7
	Big Boy	.19	18.00	28.98	3.99	13.00	187.9
	Butch	.10	16.50	24.36	4.5	11.99	25.1
	Hoppy	.08	18.00	25.00	3.99	18.99	336.6

is due to the least squared error optimization used in this study. The parameteric variation, to some extent, is reflected in the Remnant column of Table L. The above authors used the BMD 02T computer program for estimating describing function; Fig. 2.7 shows the superiority of computer algorithm used in this study over BMD 02T. Also their training procedure was similar to the one used in this study, but the paper fails to bring out the ramifications of the window size. Finally, the optimization algorithm of Section E has a definite superiority over visual "interactive-fit" used in the above reference.

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